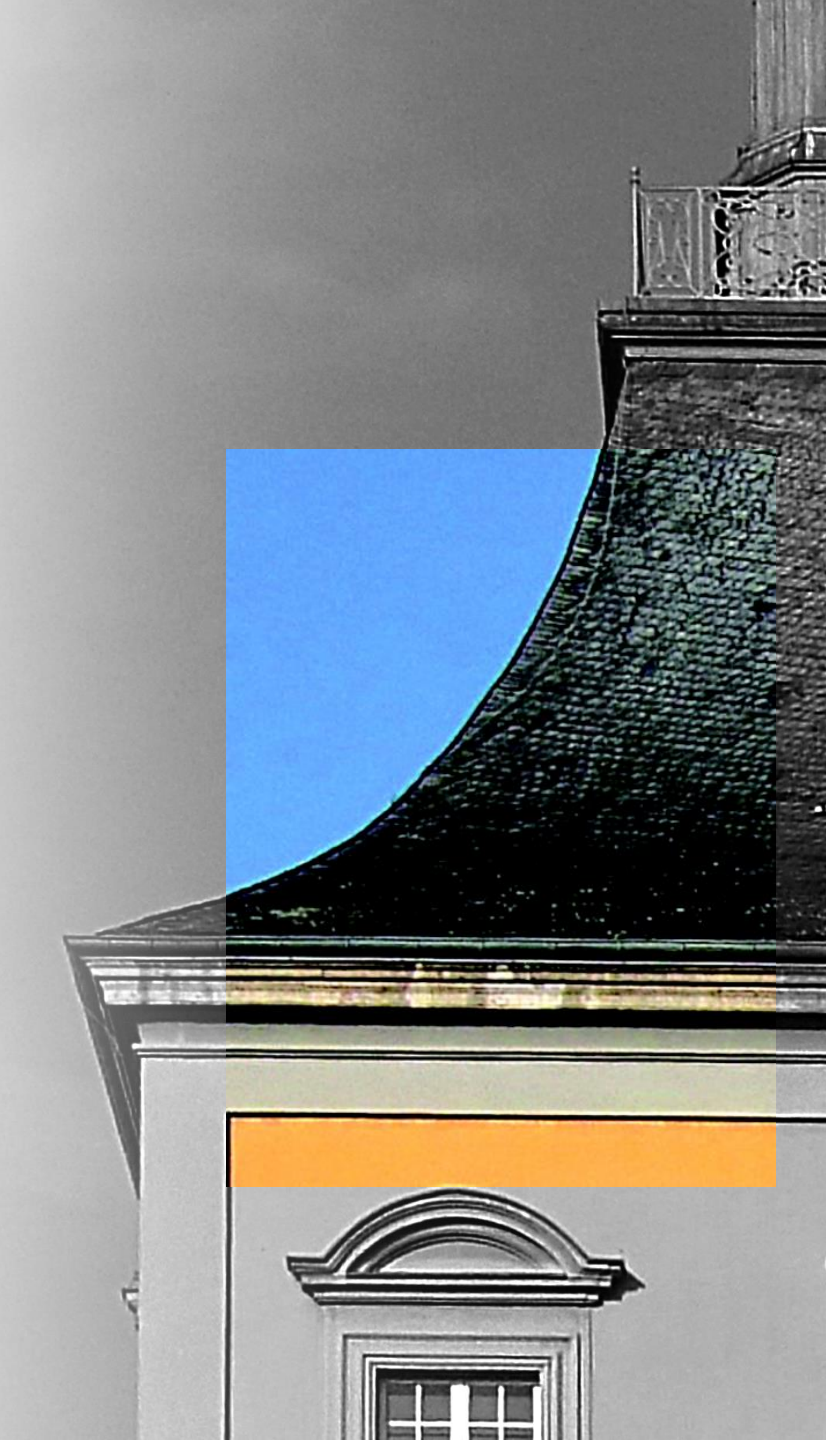
RAY TRACING FOR BABYIAXO WITH REST



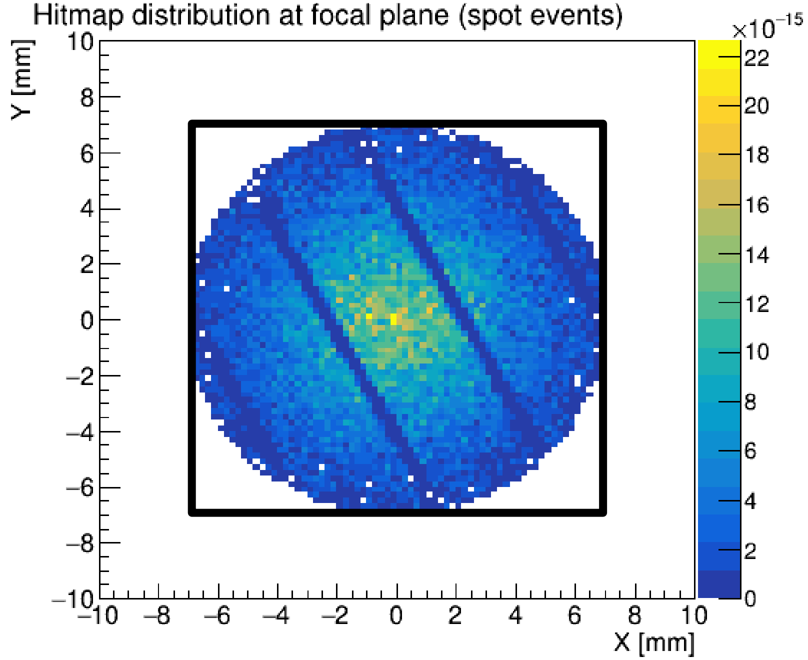
Johanna von Oy

Axion++ workshop

26.09.23

BABYIAXO AT DESY

- BabyIAXO will be built at DESY
- Until then: simmulations through ray tracing



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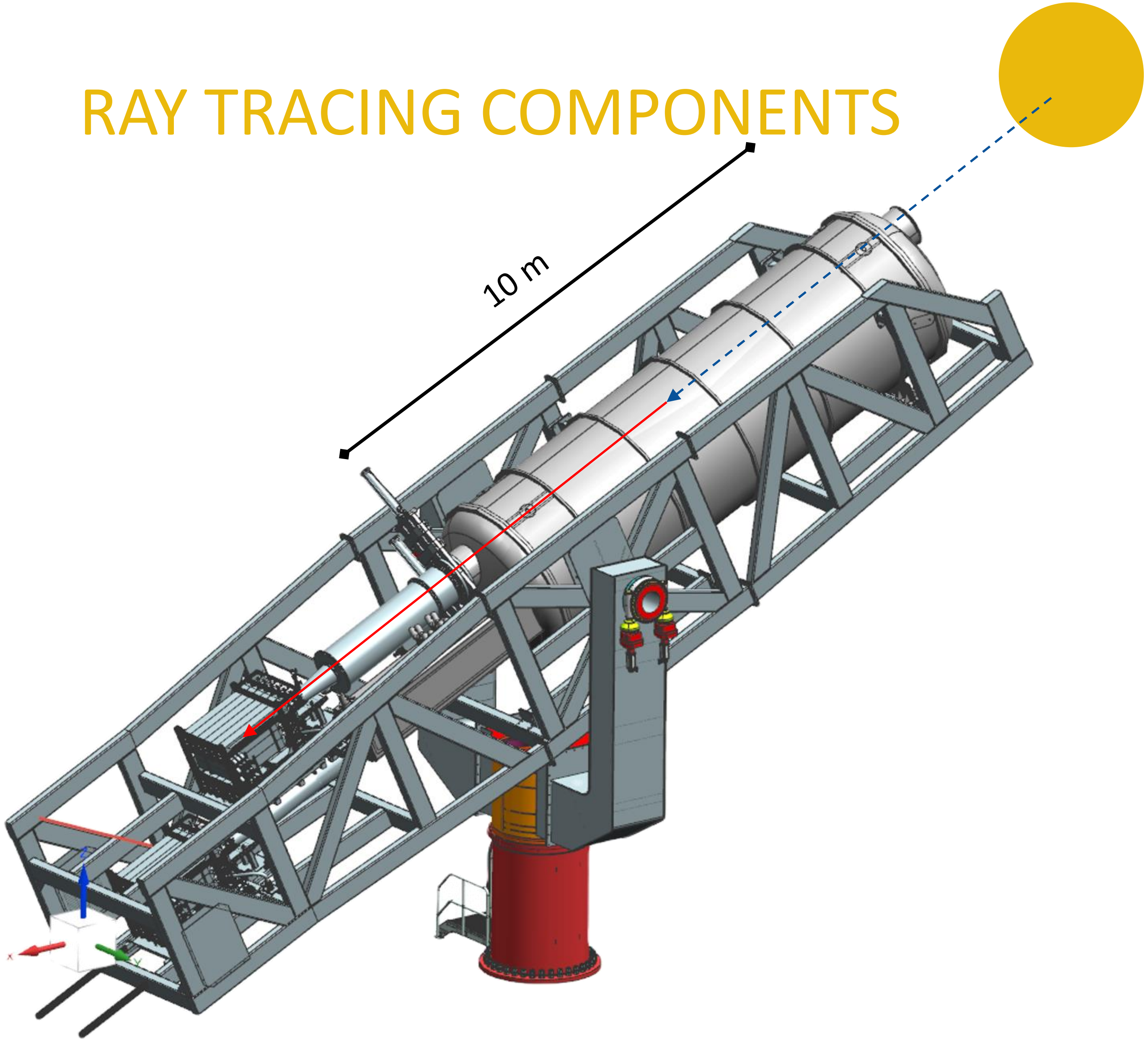
MOTIVATION RAY TRACER AND REST

- Adjust the axion model to compare the simulation with future results
- Adjust the position of the telescope components to understand their acceptance range

Rare Event
Searches Toolkit
software

- Mainly written in C++ and fully integrated with ROOT I/O interface
- Contains other libraries for data processing and analysis

RAY TRACING COMPONENTS



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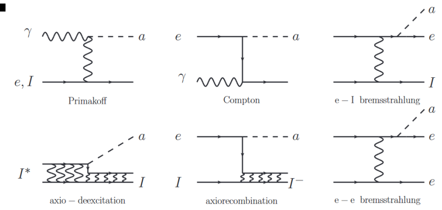
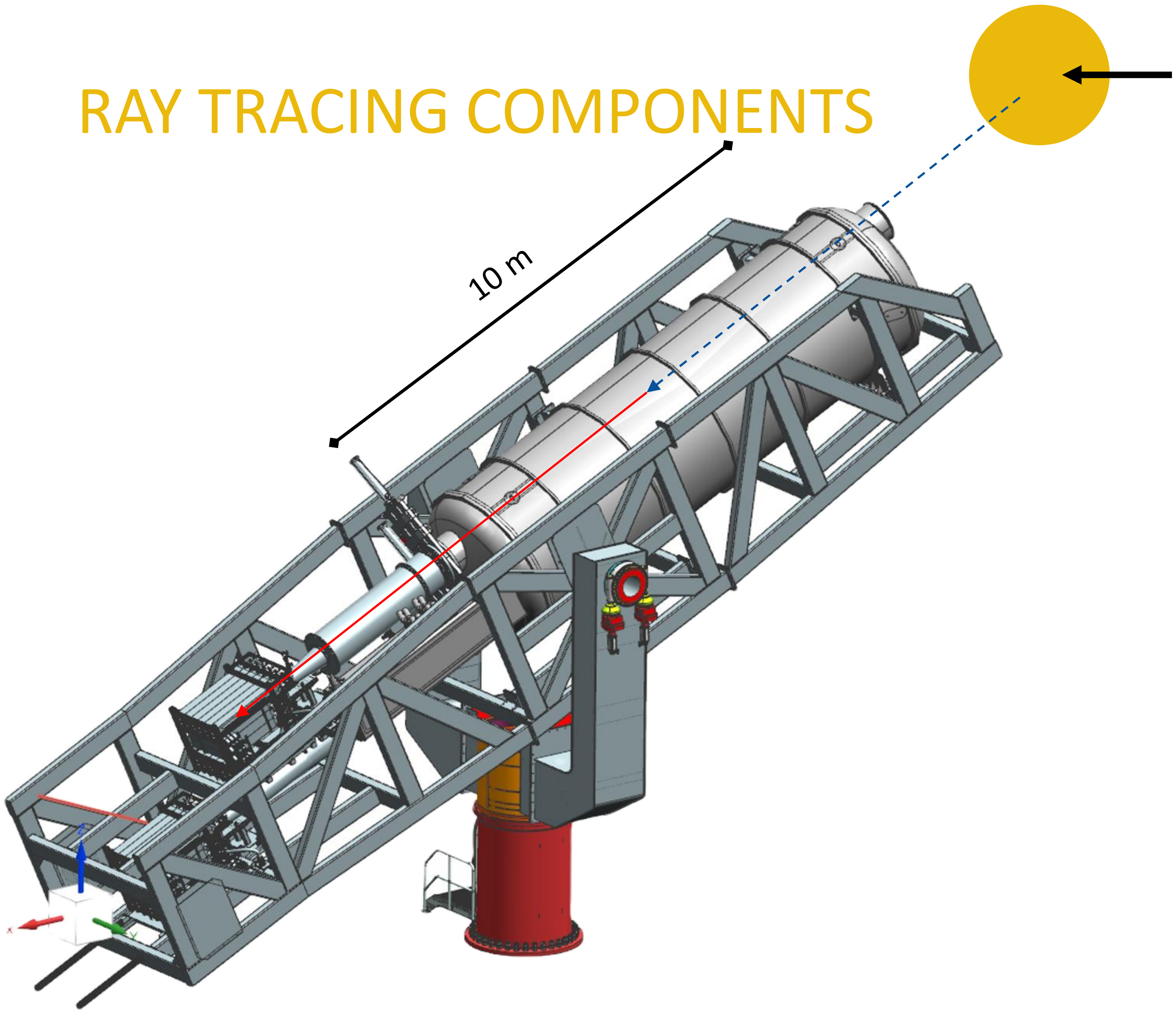
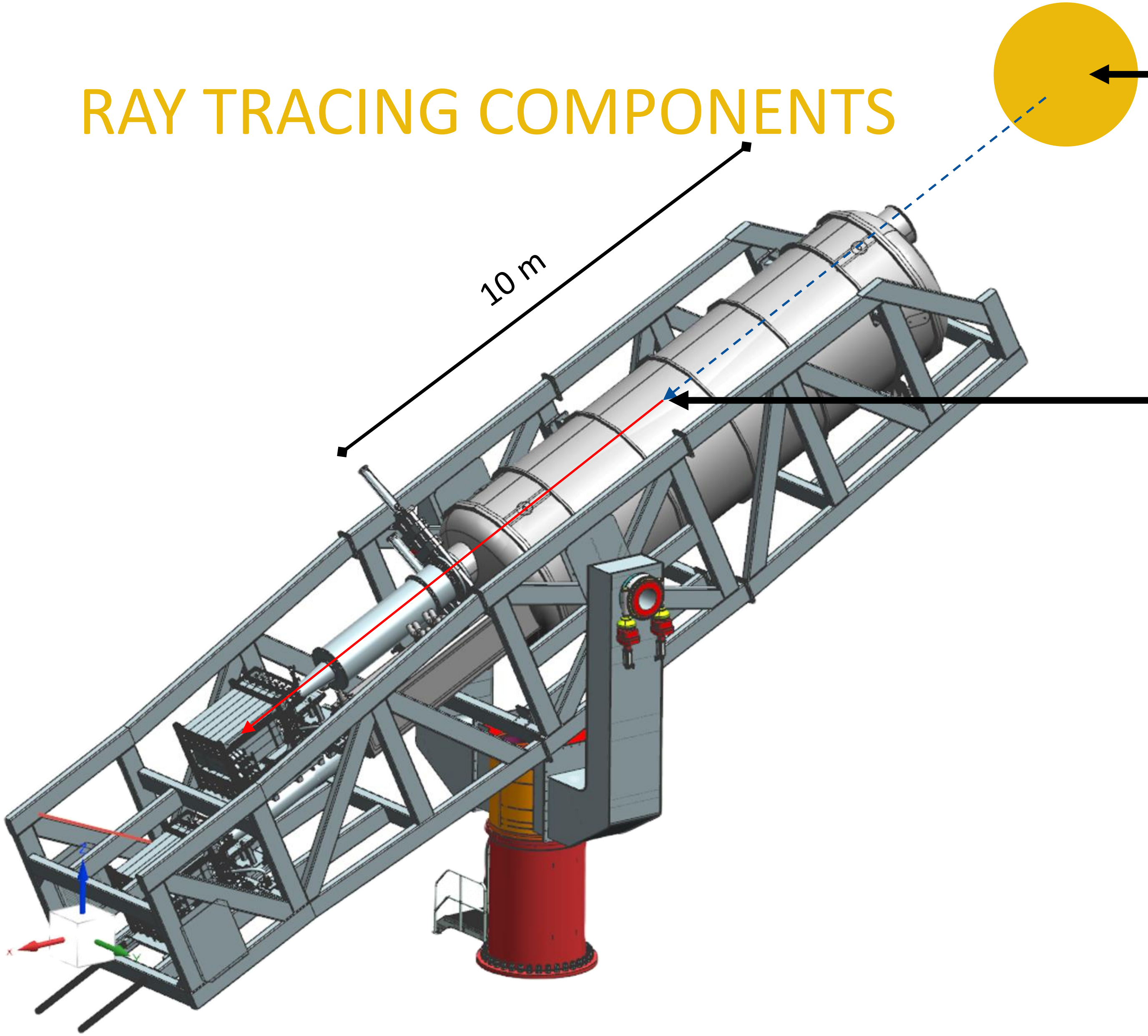
RAY TRACING COMPONENTS

Axion production in the sun

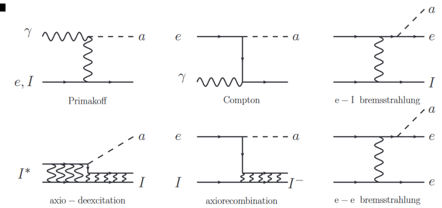




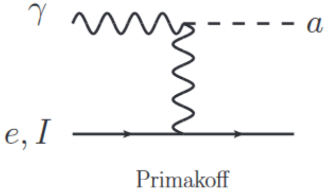
RAY TRACING COMPONENTS



Axion production in the sun

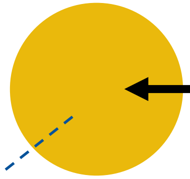


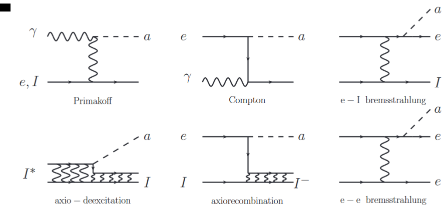
Axions couple to photons in magnetic field

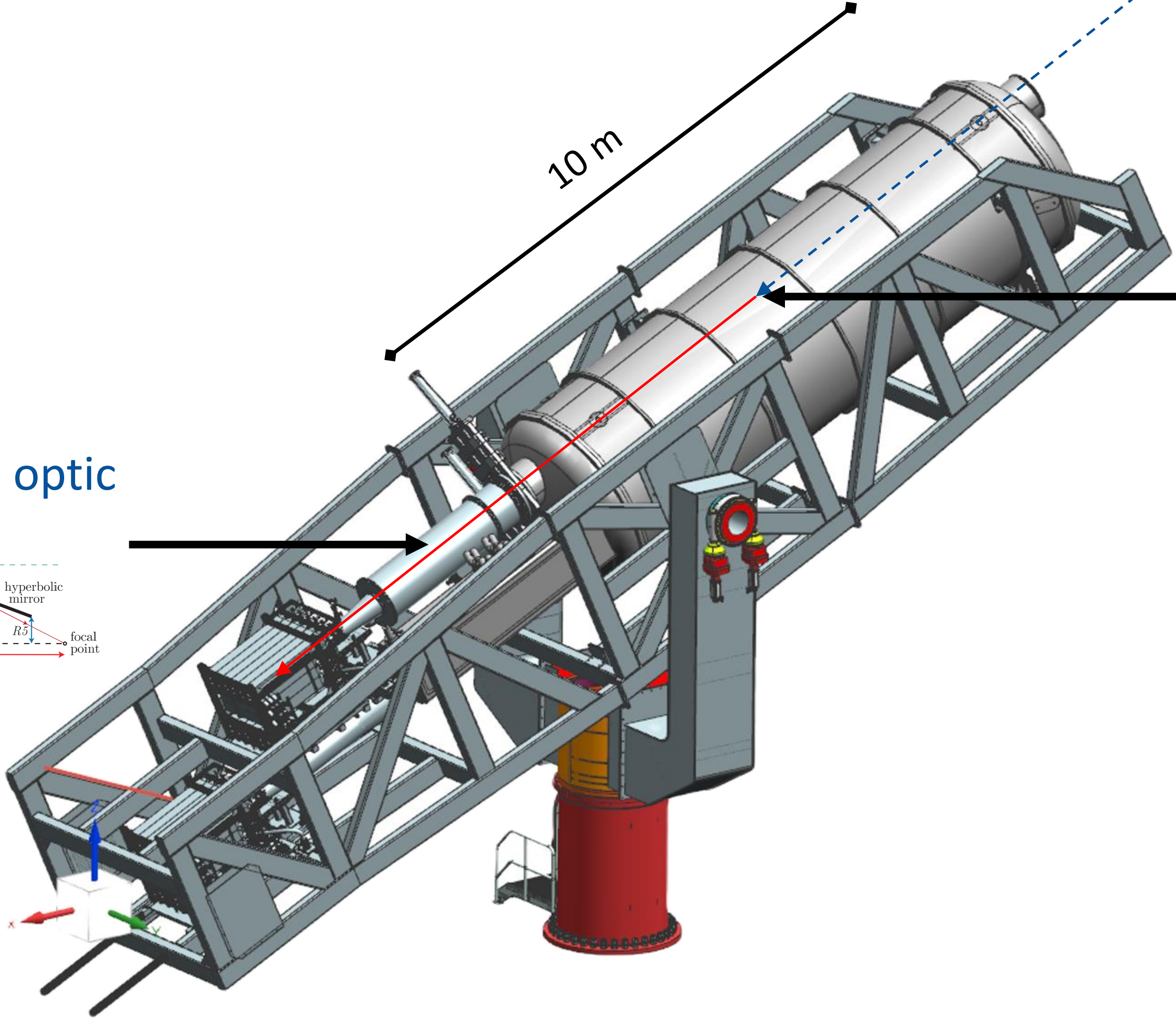


RAY TRACING COMPONENTS

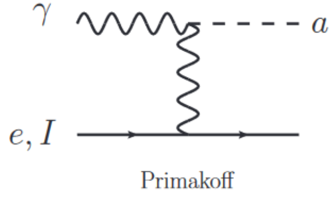
Axion production in the sun



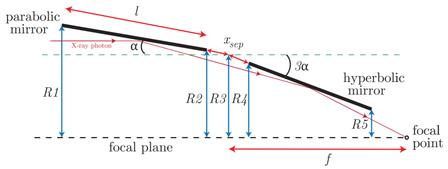




Axions couple to photons in magnetic field



Focus of X-rays in optic



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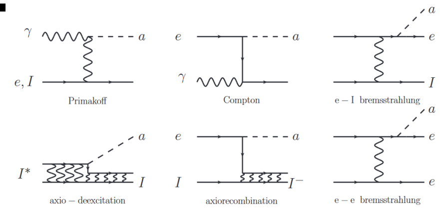
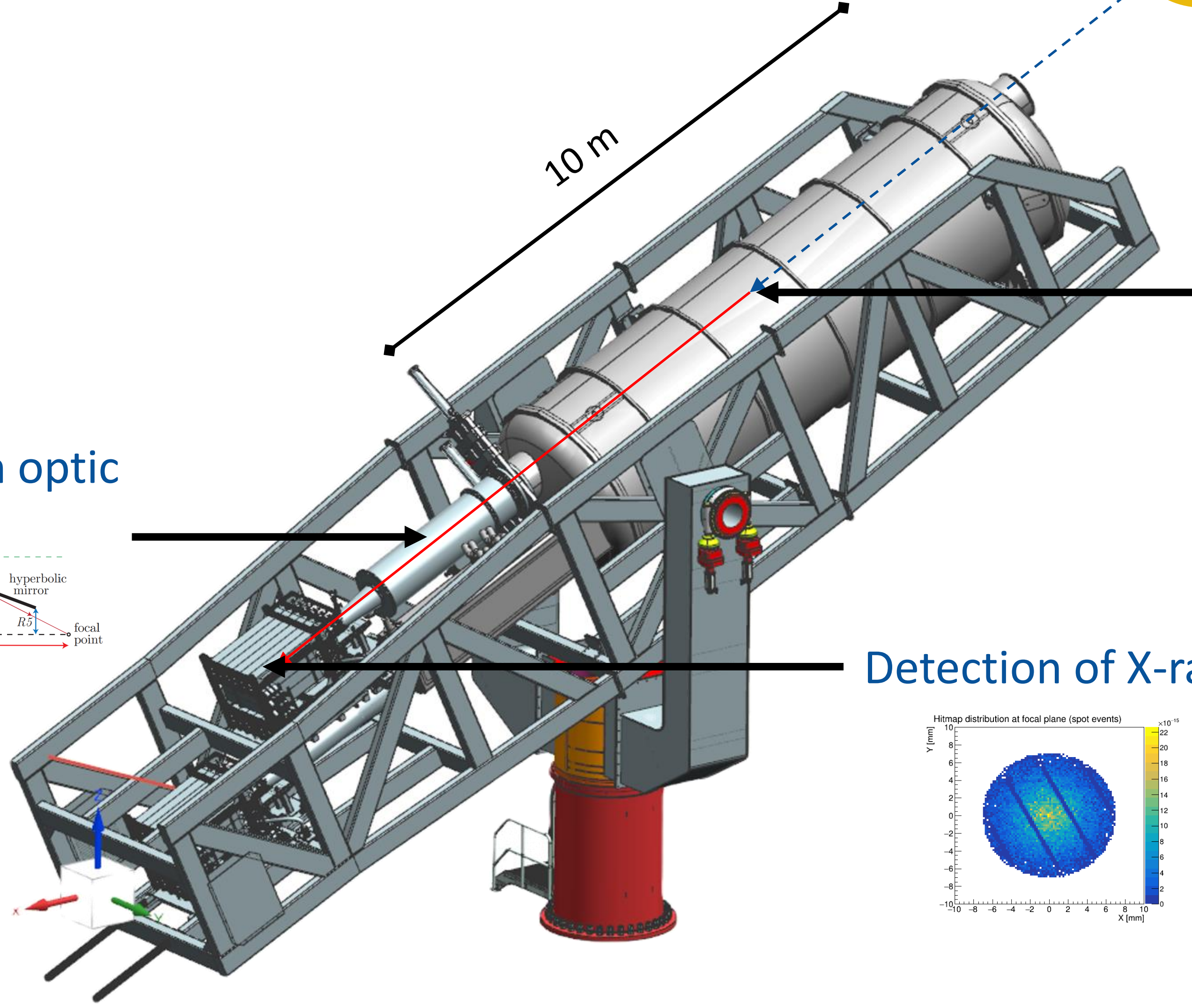
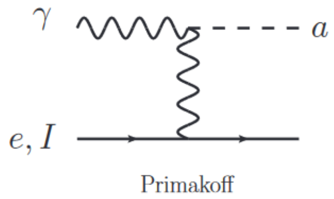
RAY TRACING COMPONENTS

Axion production in the sun

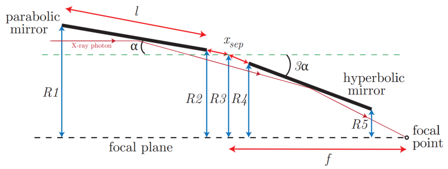




Axions couple to photons in magnetic field

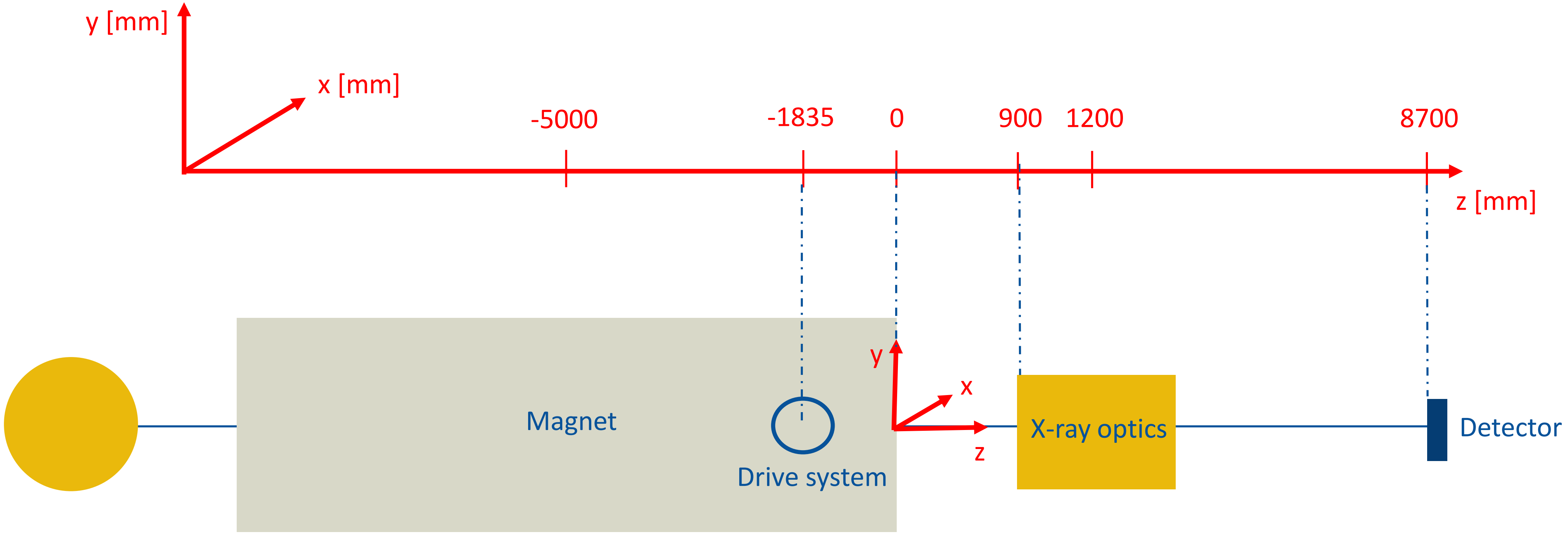


Focus of X-rays in optic

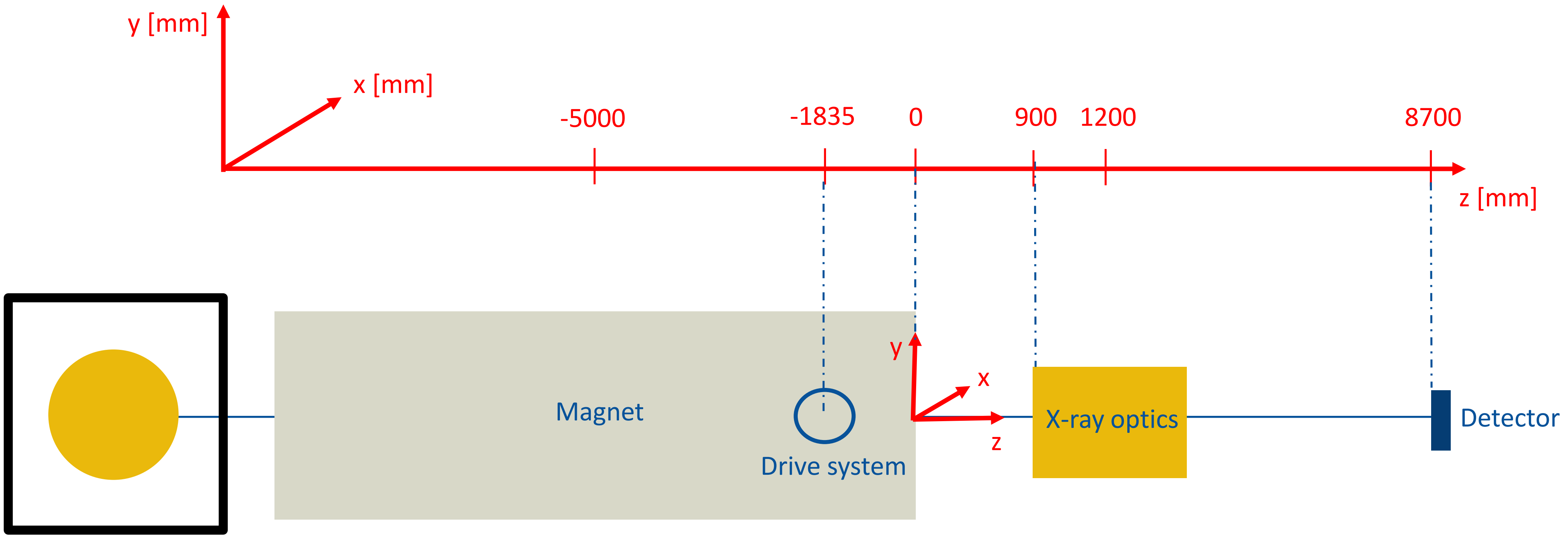


Detection of X-rays

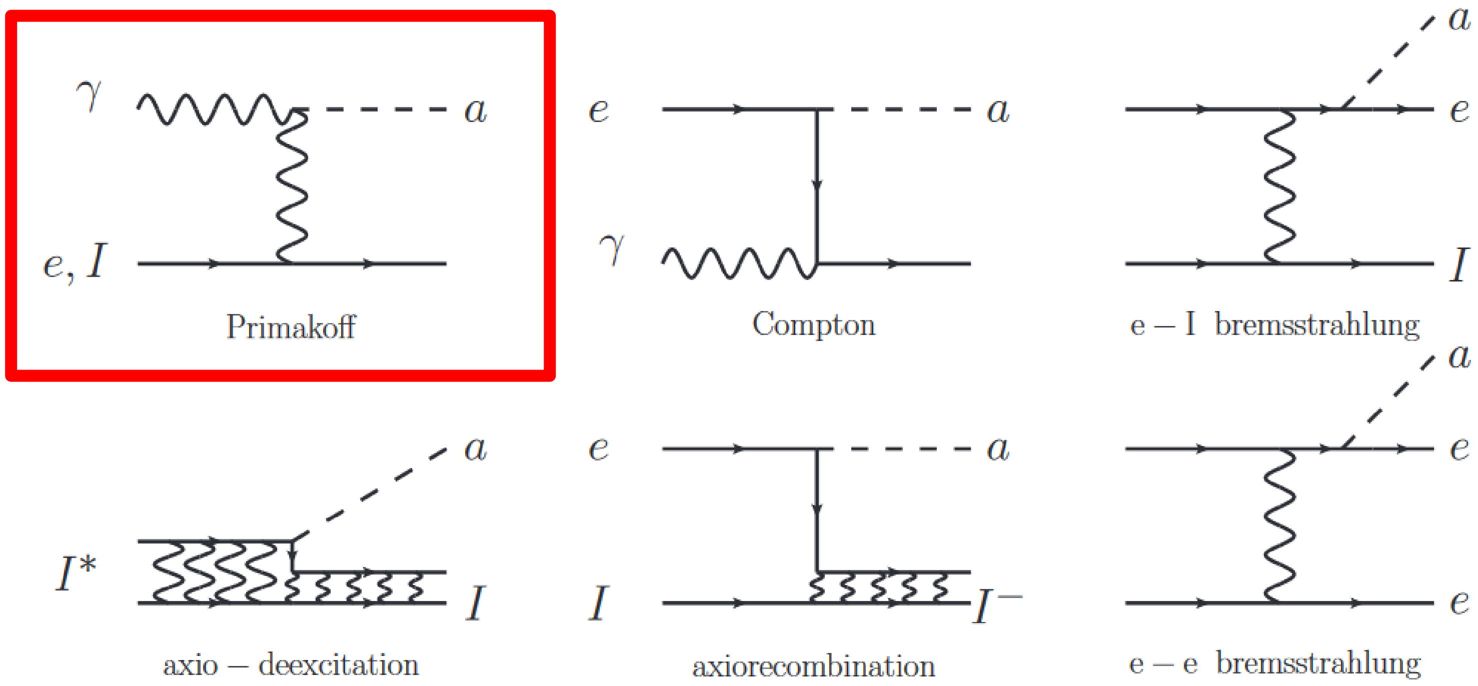
BABYIAXO SETUP



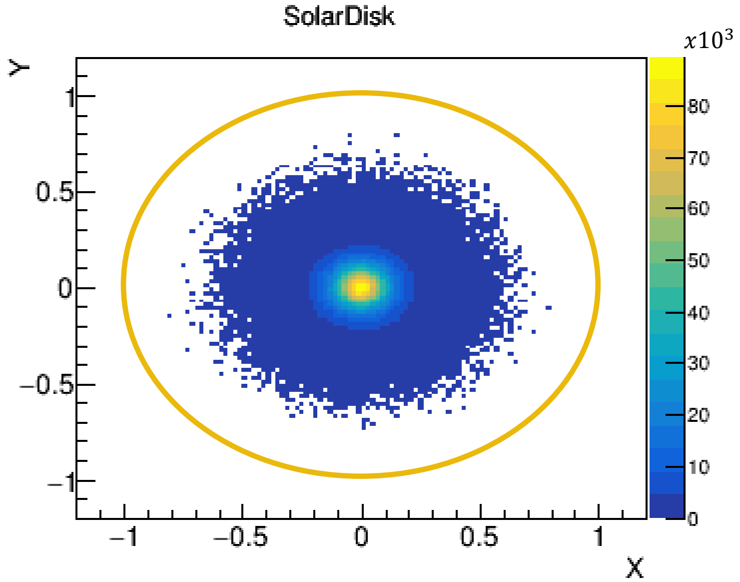
BABYIAXO – SOLAR AXIONS



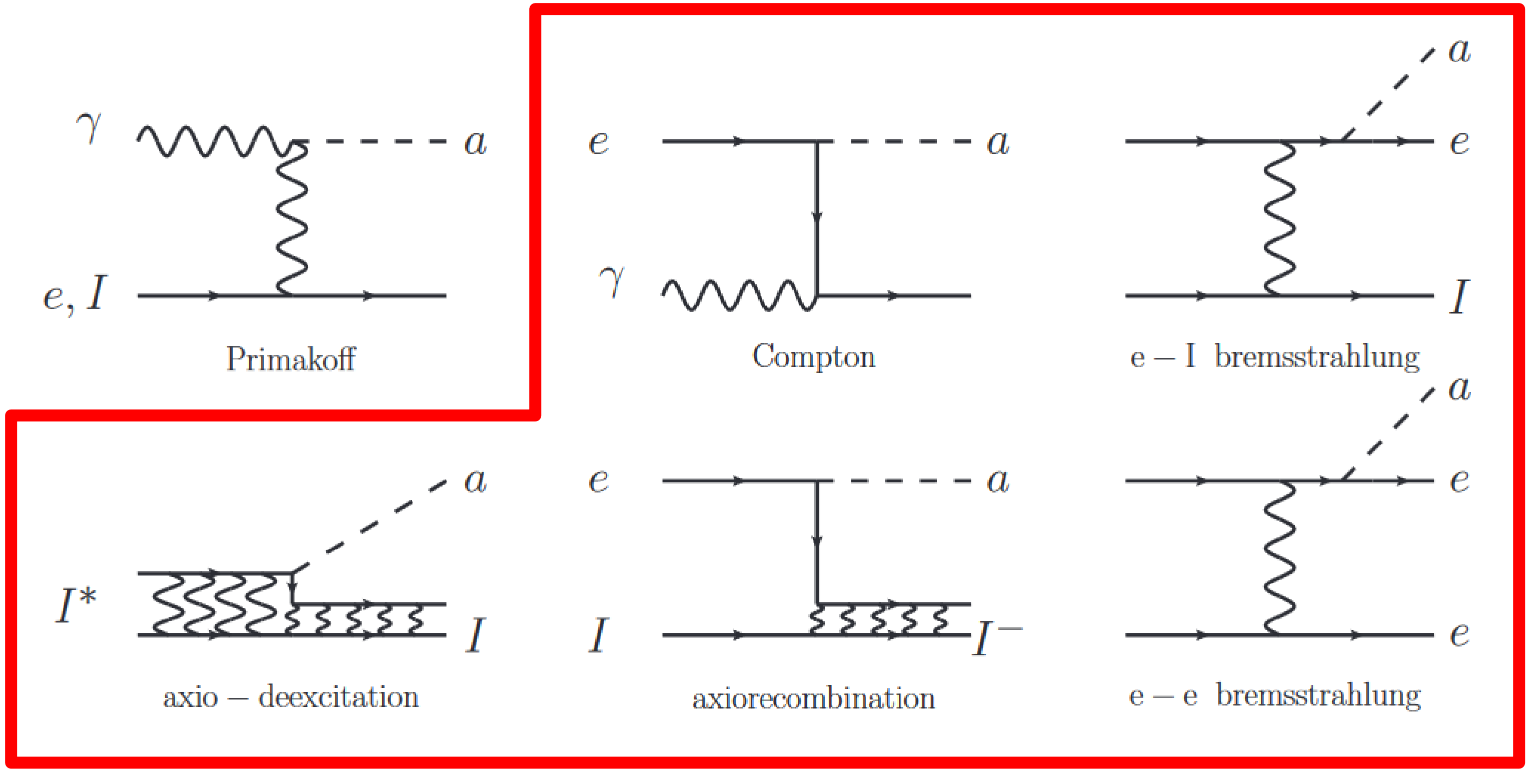
SOLAR AXIONS – RADIAL DISTRIBUTION



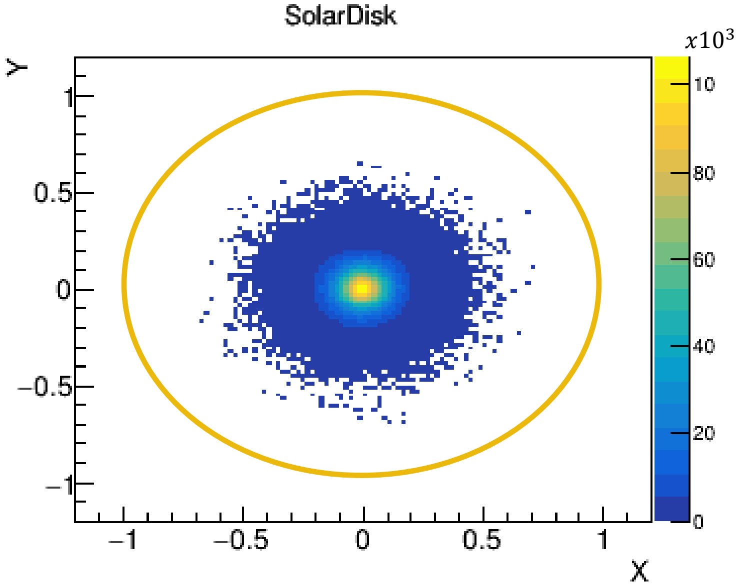
Radial distribution of Primakoff axion flux in sun



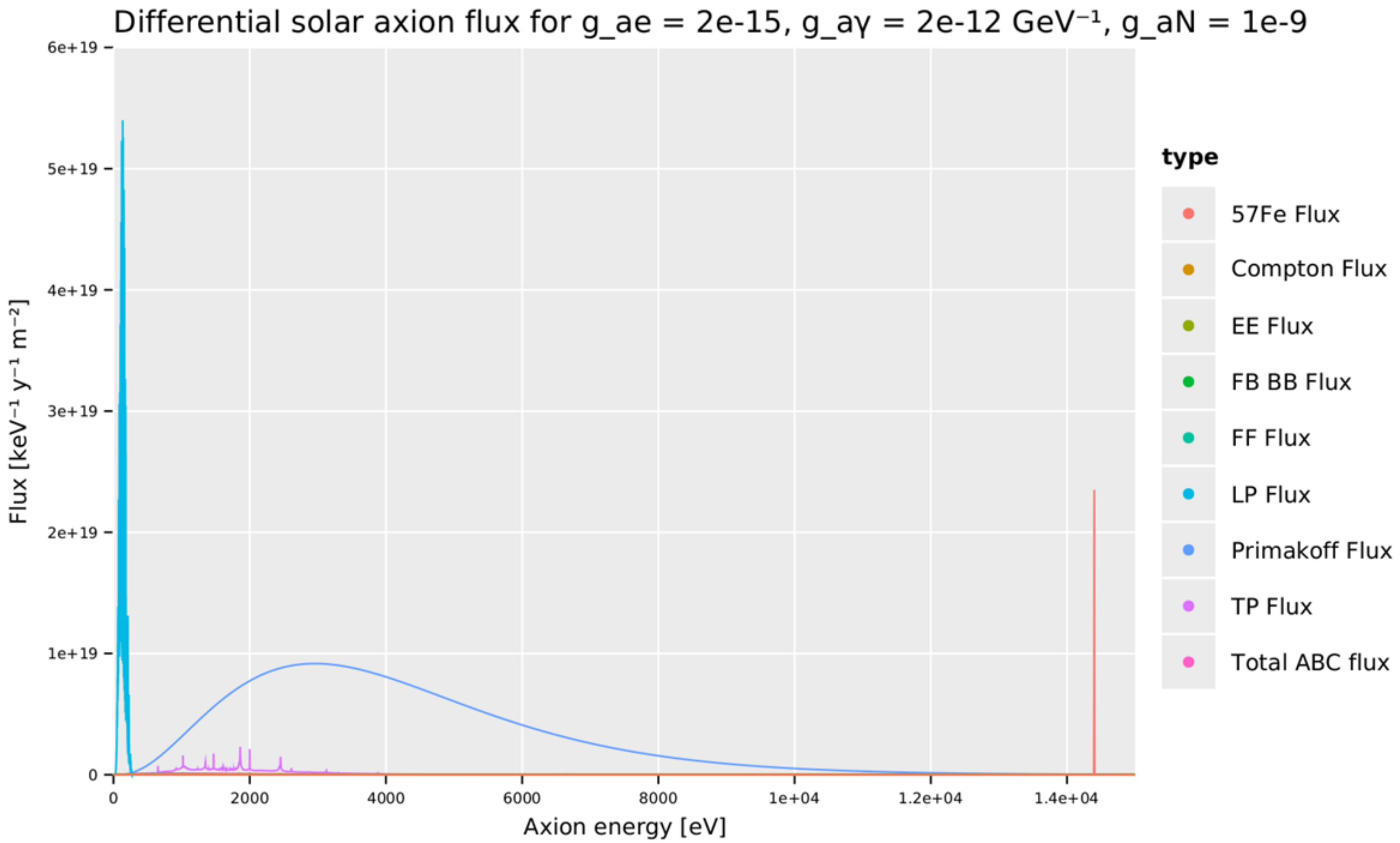
SOLAR AXIONS – RADIAL DISTRIBUTION



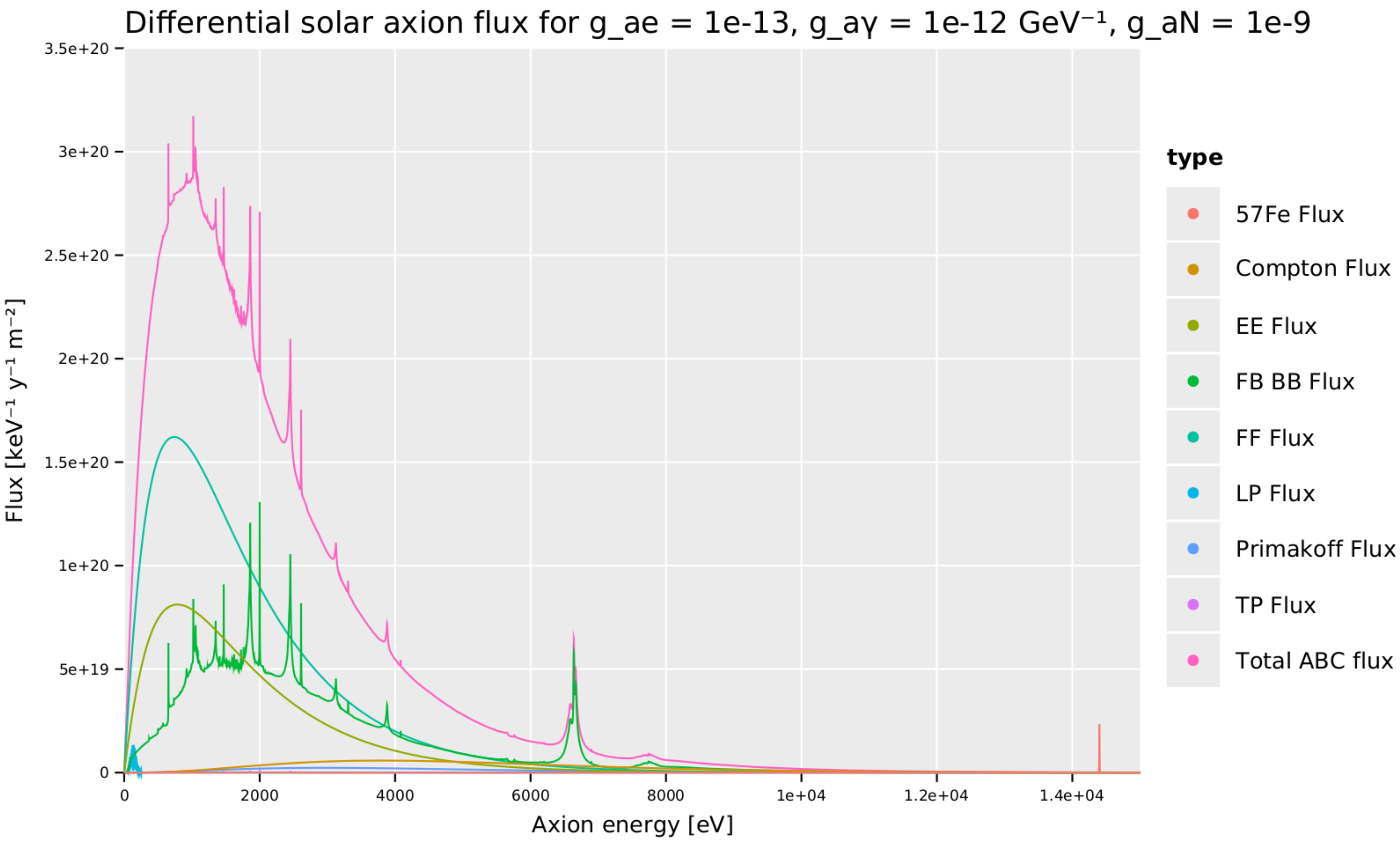
Radial distribution of ABC axion flux in sun



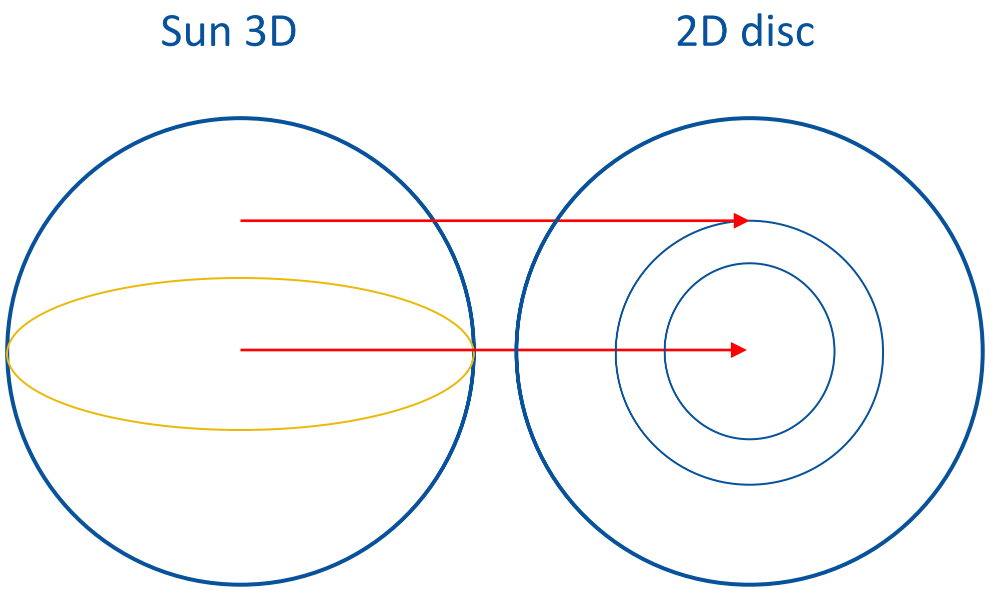
SOLAR AXION – KSVZ ENERGY DISTRIBUTION



SOLAR AXION – DFSZ ENERGY DISTRIBUTION

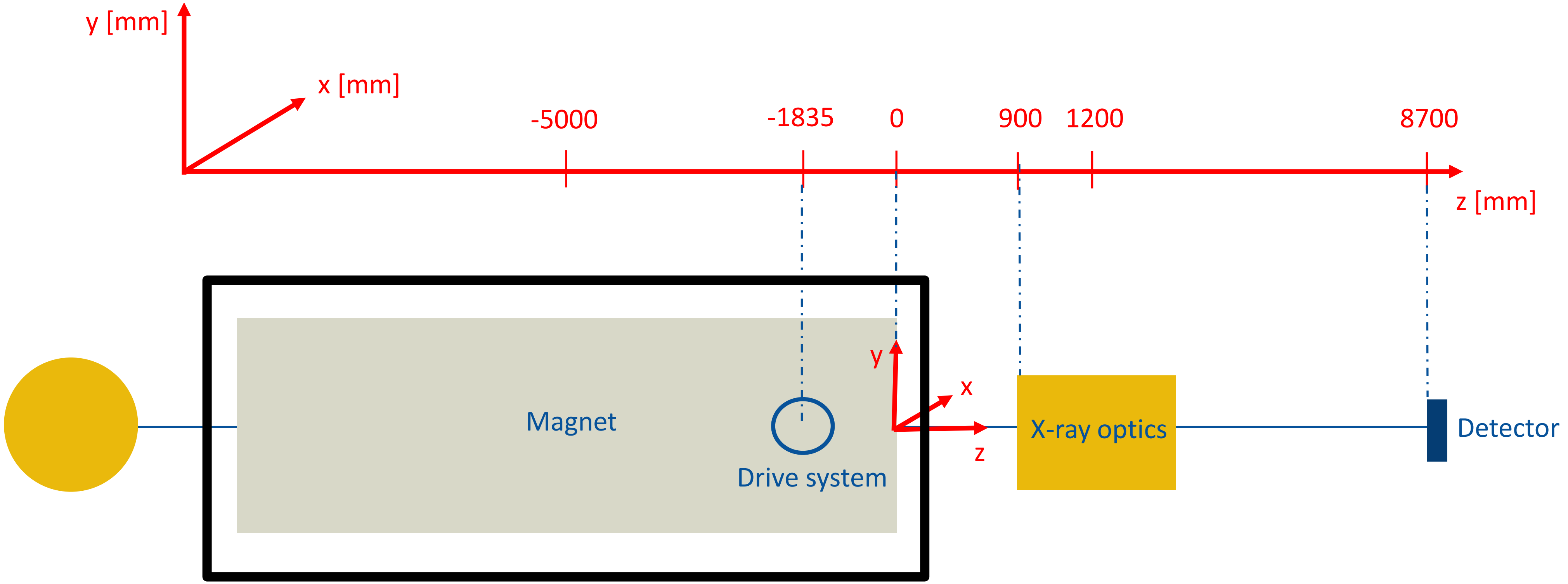


GENERATING AXIONS FROM THE SUN

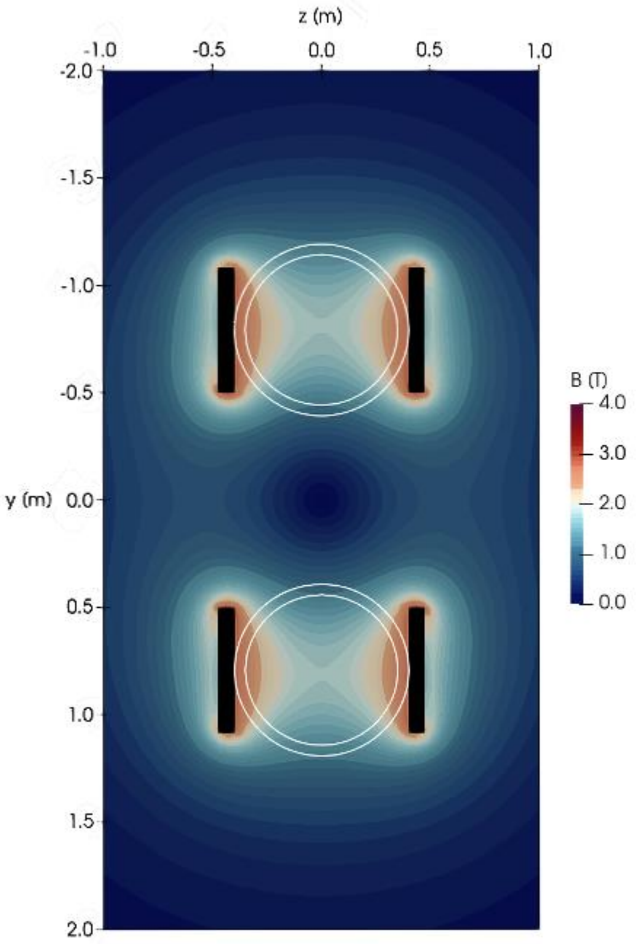


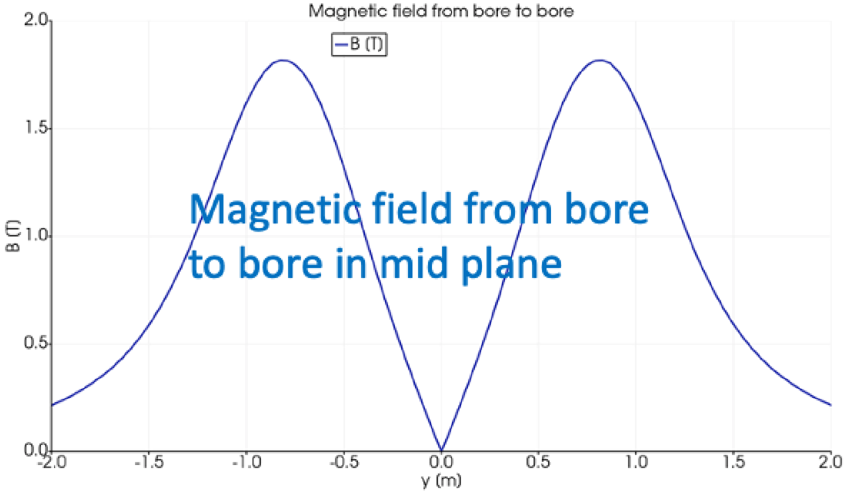
1. Integrate over the sun for each radius
2. Get random radius and energy for each axion biased by the calculated flux

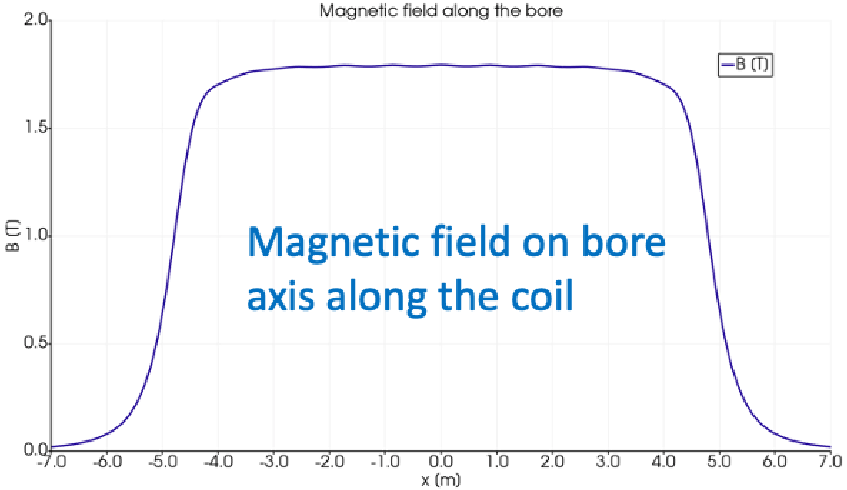
BABYIAXO – THE MAGNET



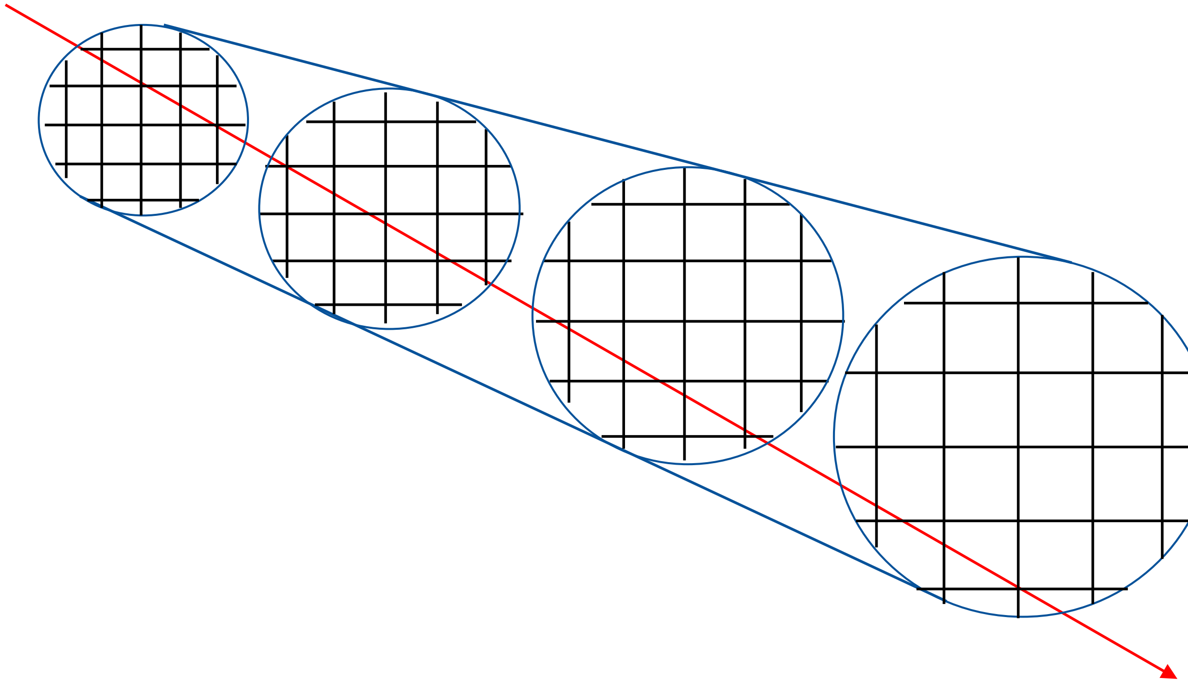
MAGNETIC FIELD





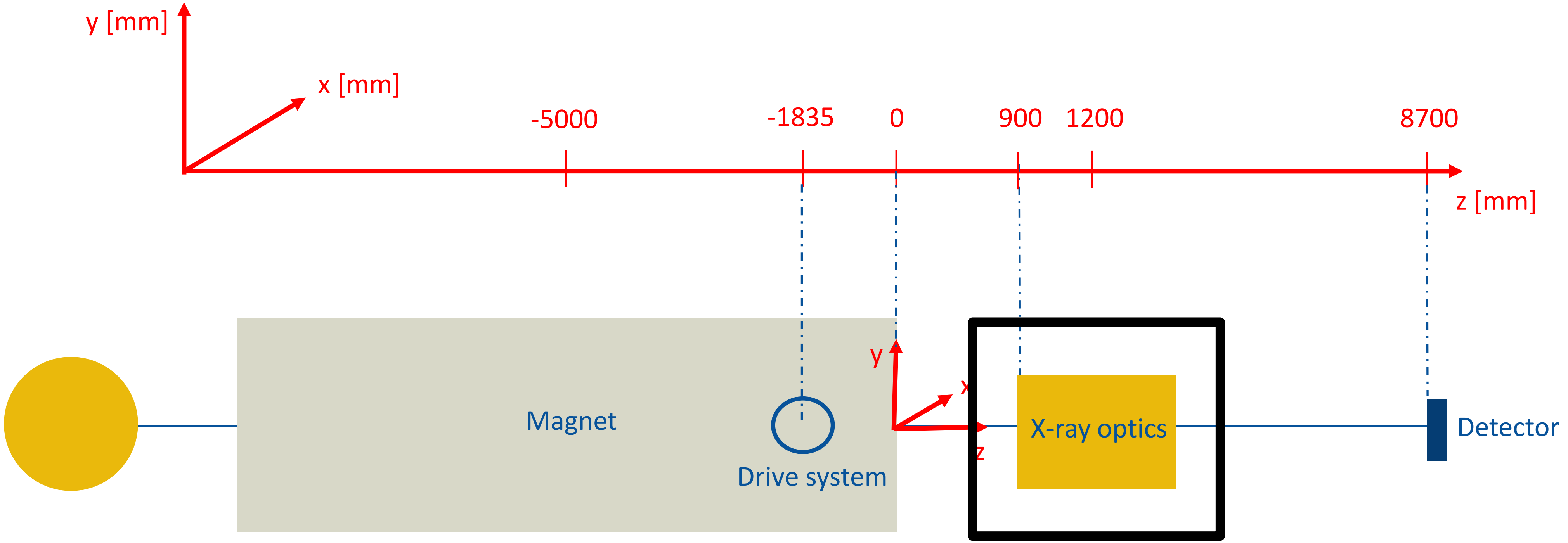


MAGNETIC FIELD IMPLEMENTATION



1. Get magnetic field on grid-vector intersection points
2. Integrate magnetic field over vector
3. Photon production probability: $P_{a\to\gamma} = \frac{1}{4}(g_{a\gamma}BL)^2$

BABYIAXO – X-RAY OPTICS



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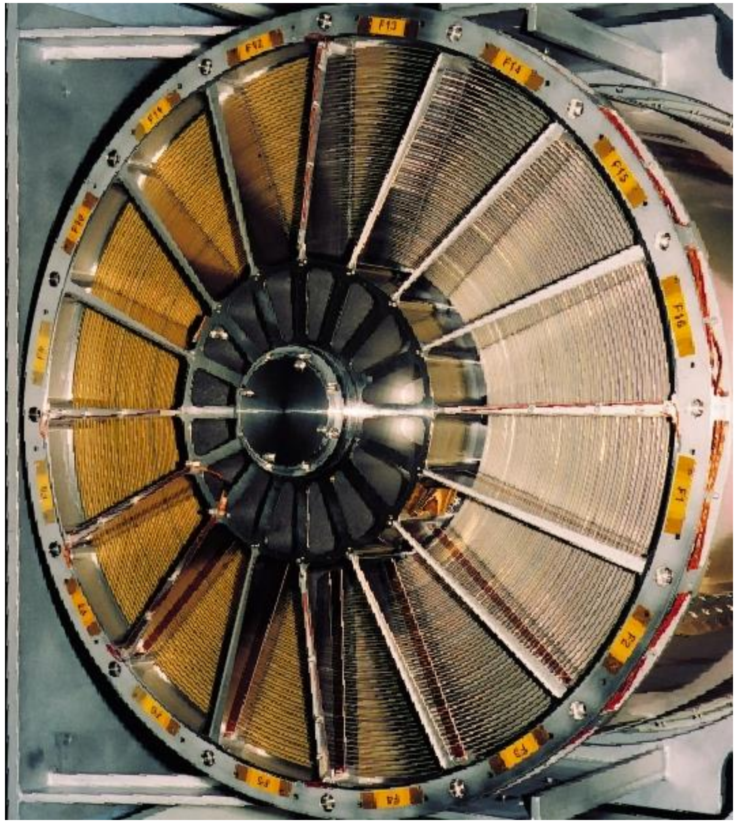
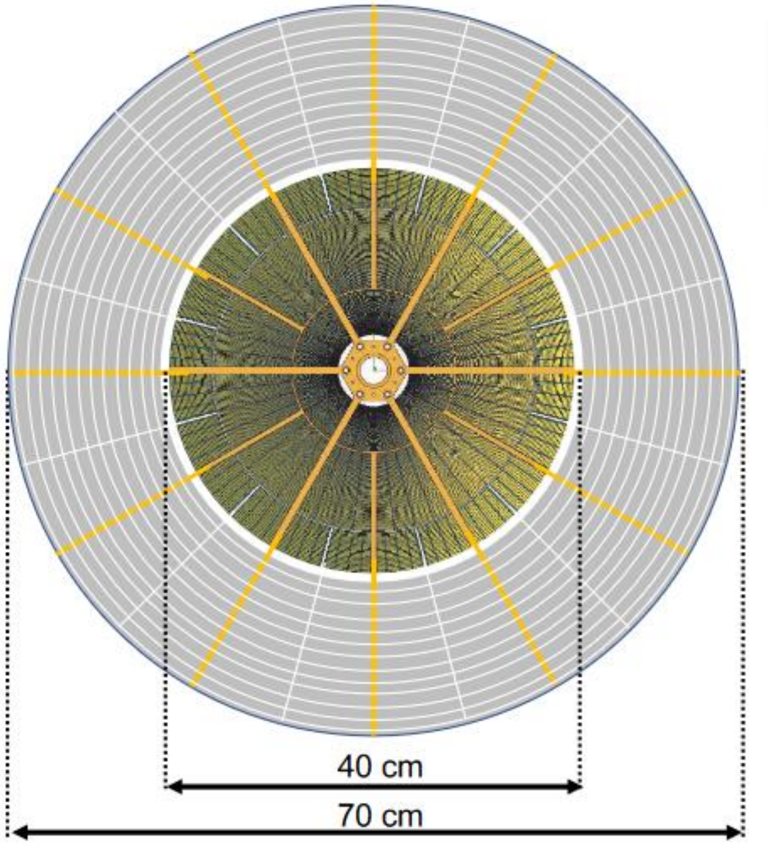
X-RAY OPTICS

The XMM optics built for the XMM-Newton space mission



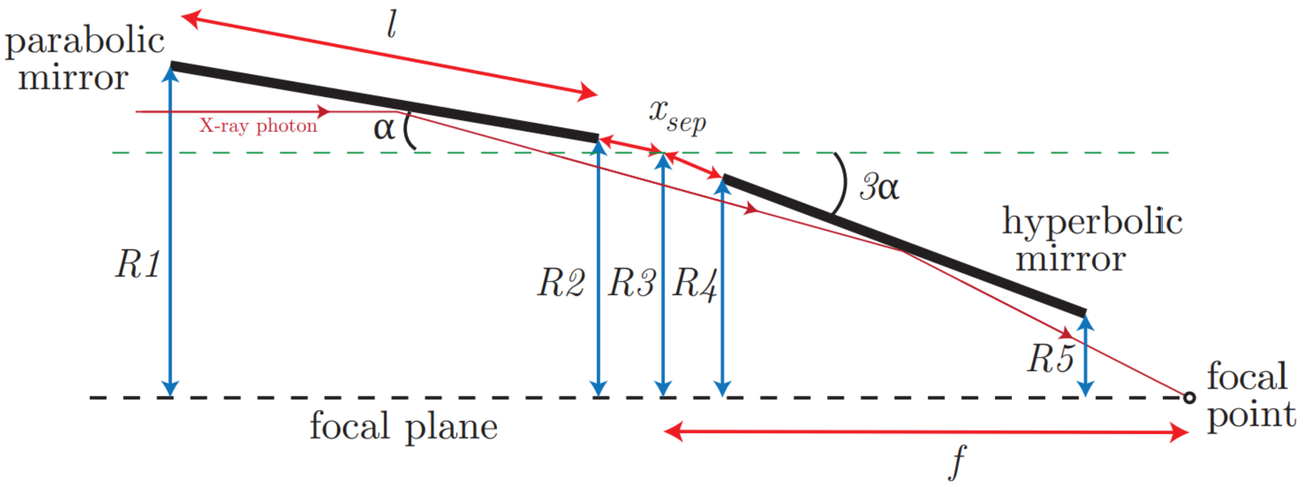
The custom BabyIAXO optics consisting of an inner optics and an outer optics



IAXO collaboration 2020, arXiv:2010.12076

WOLTER I OPTICS

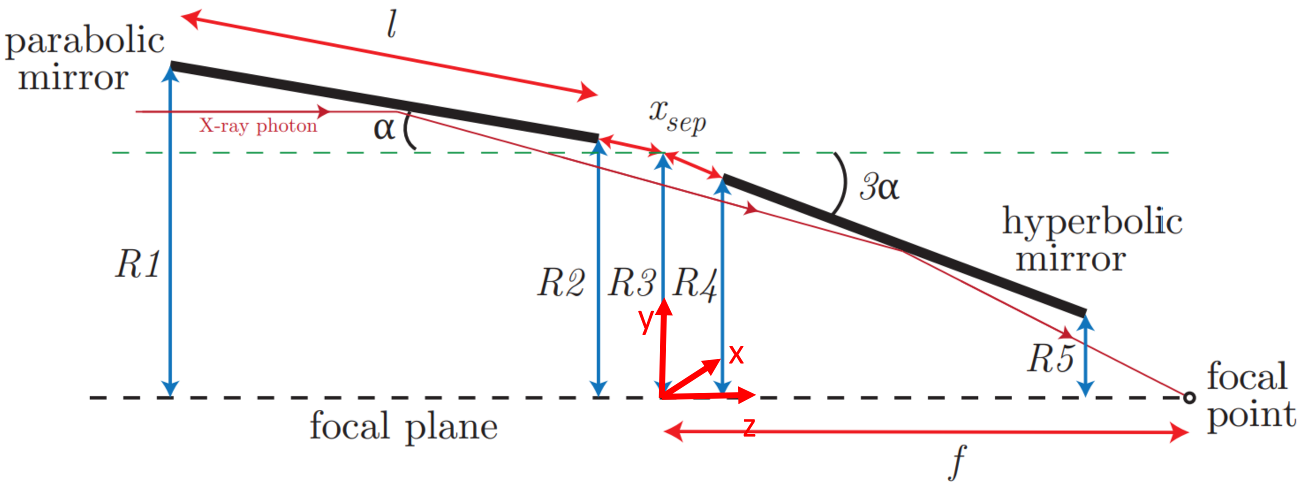
A Wolter I optic principle from the side



1. Find interaction point
2. Turn X-ray vector in regards to the respective normal vector

WOLTER I OPTICS

A Wolter I optic principle from the side



1. Find interaction point
2. Turn X-ray vector in regards to the respective normal vector

Wolter I: Parabolic mirror function

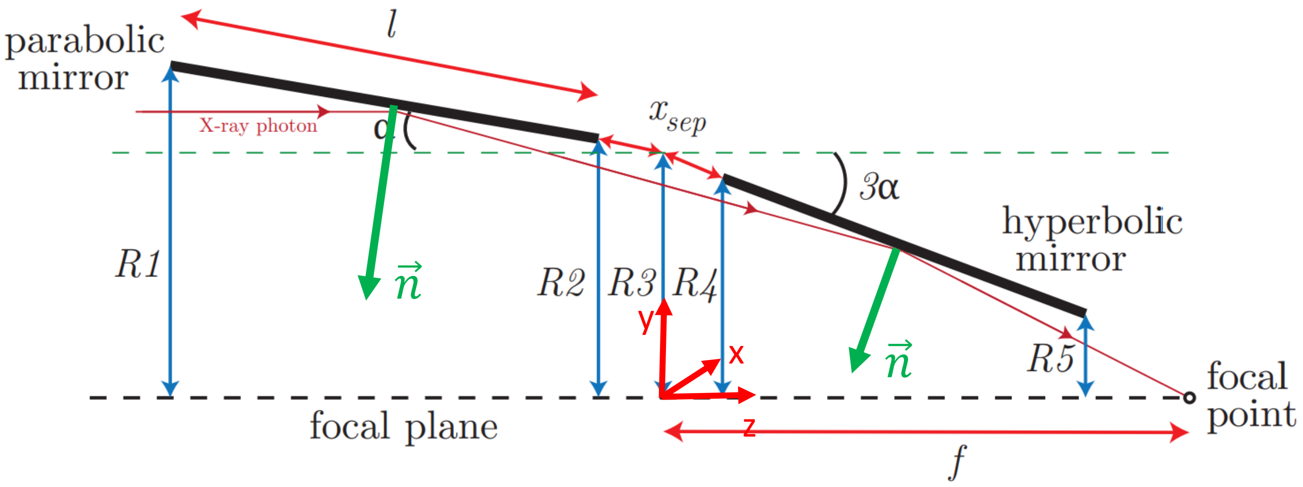
$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(\alpha) \cdot z$$

Wolter I: Hyperbolic mirror function

$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(3\alpha) \cdot \left(z + \frac{z^2}{f + R3 \cdot \cot(2\alpha)}\right)$$

WOLTER I OPTICS

A Wolter I optic principle from the side



1. Find interaction point
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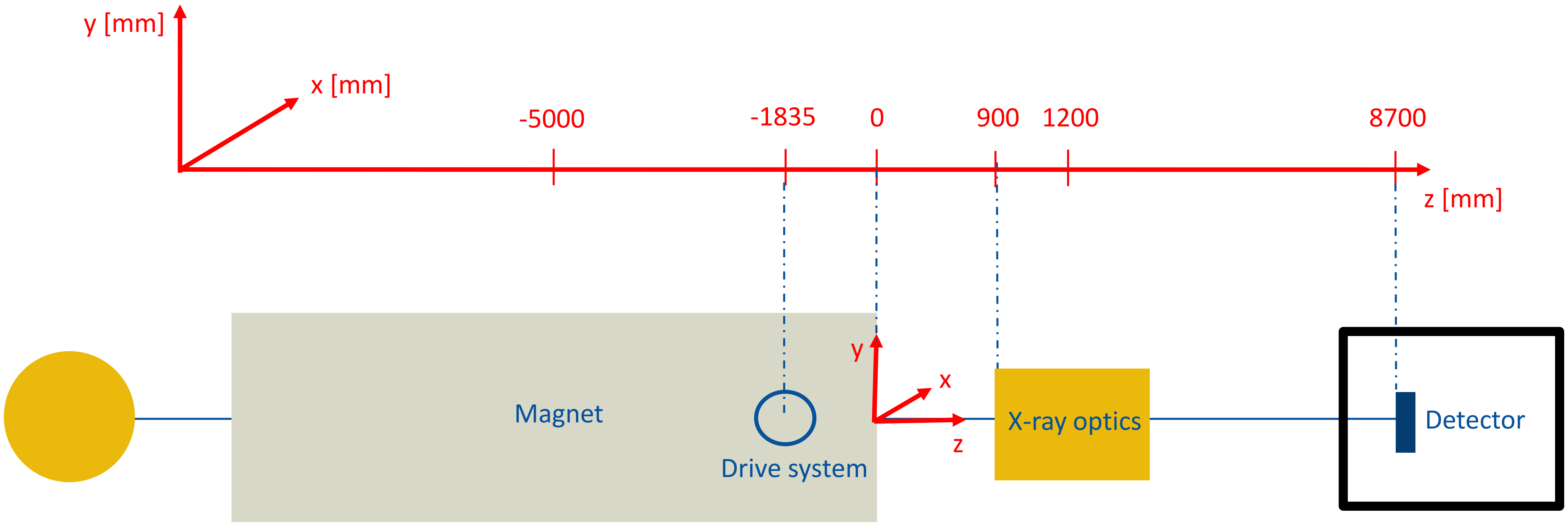
Wolter I: Parabolic mirror function

$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(\alpha) \cdot z$$

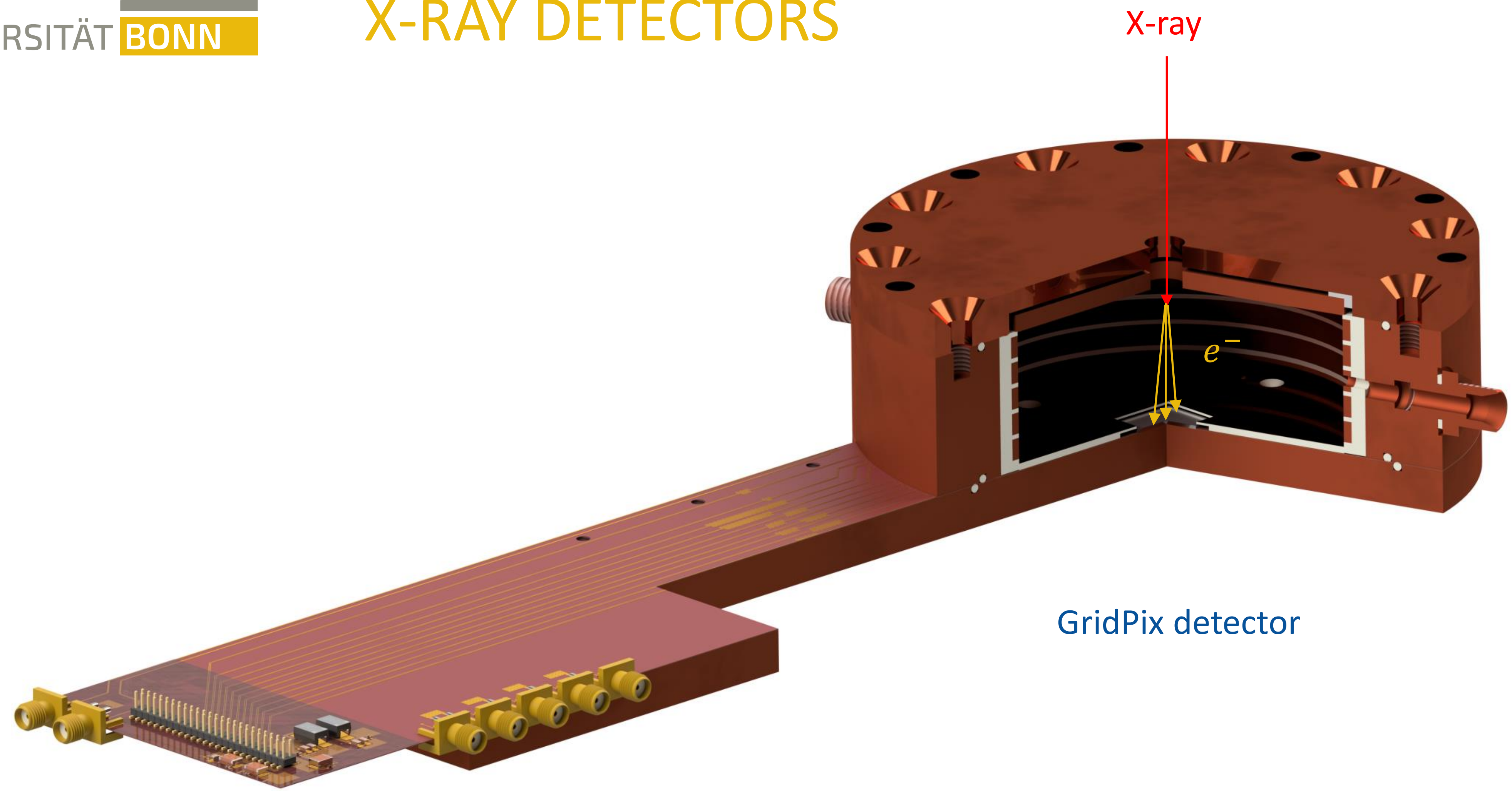
Wolter I: Hyperbolic mirror function

$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(3\alpha) \cdot \left(z + \frac{z^2}{f + R3 \cdot \cot(2\alpha)}\right)$$

BABYIAXO – DETECTORS



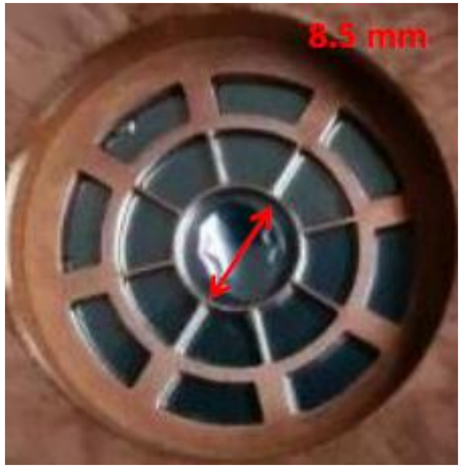
X-RAY DETECTORS



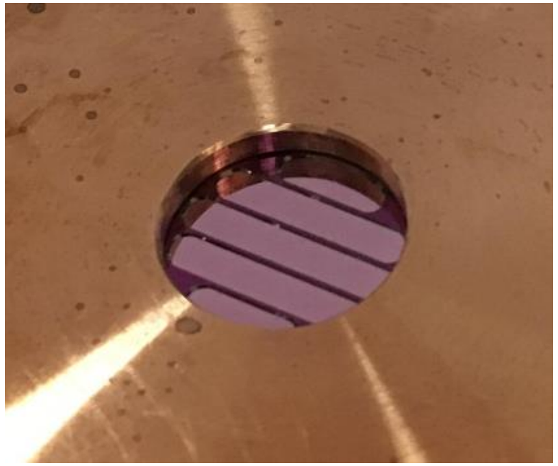
GridPix detector

DETECTOR WINDOWS AND MASKS

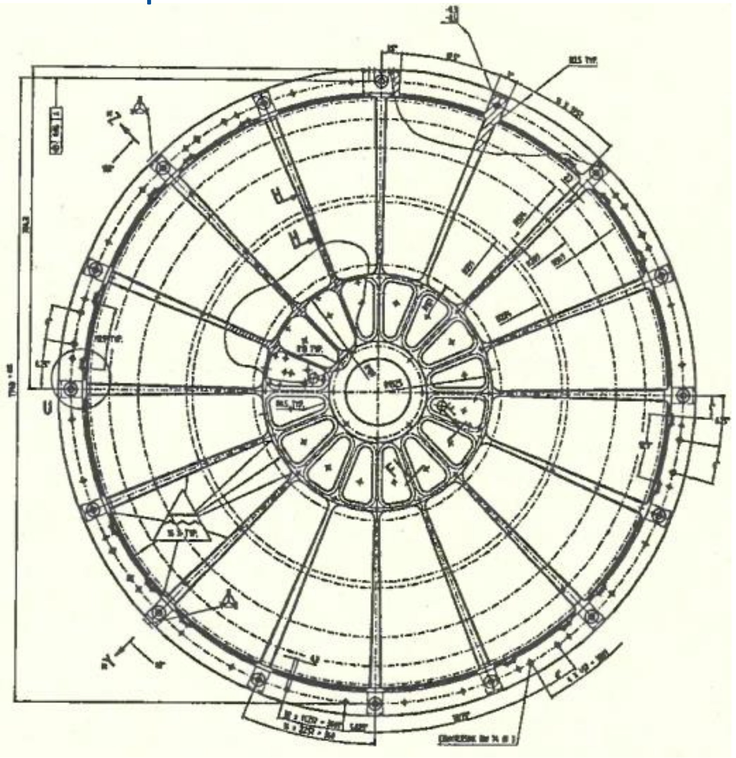
Mylar window



A vacuum tight Si3N4 window

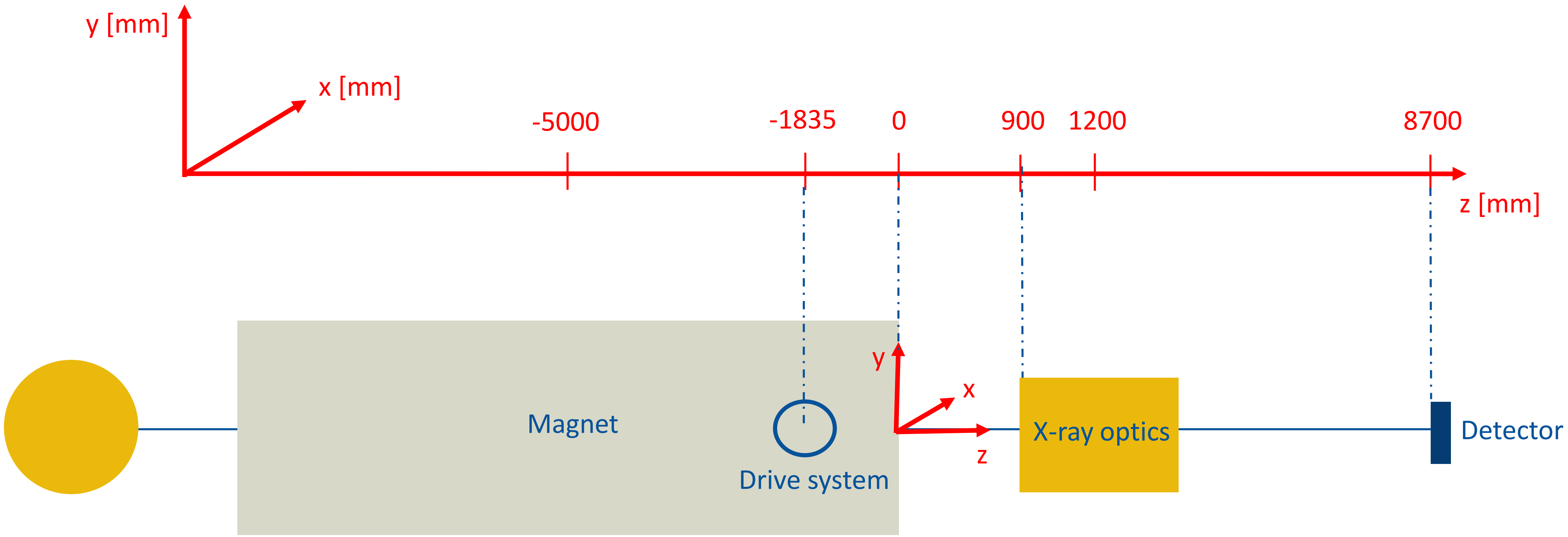


The spider structure in front of the XMM optics



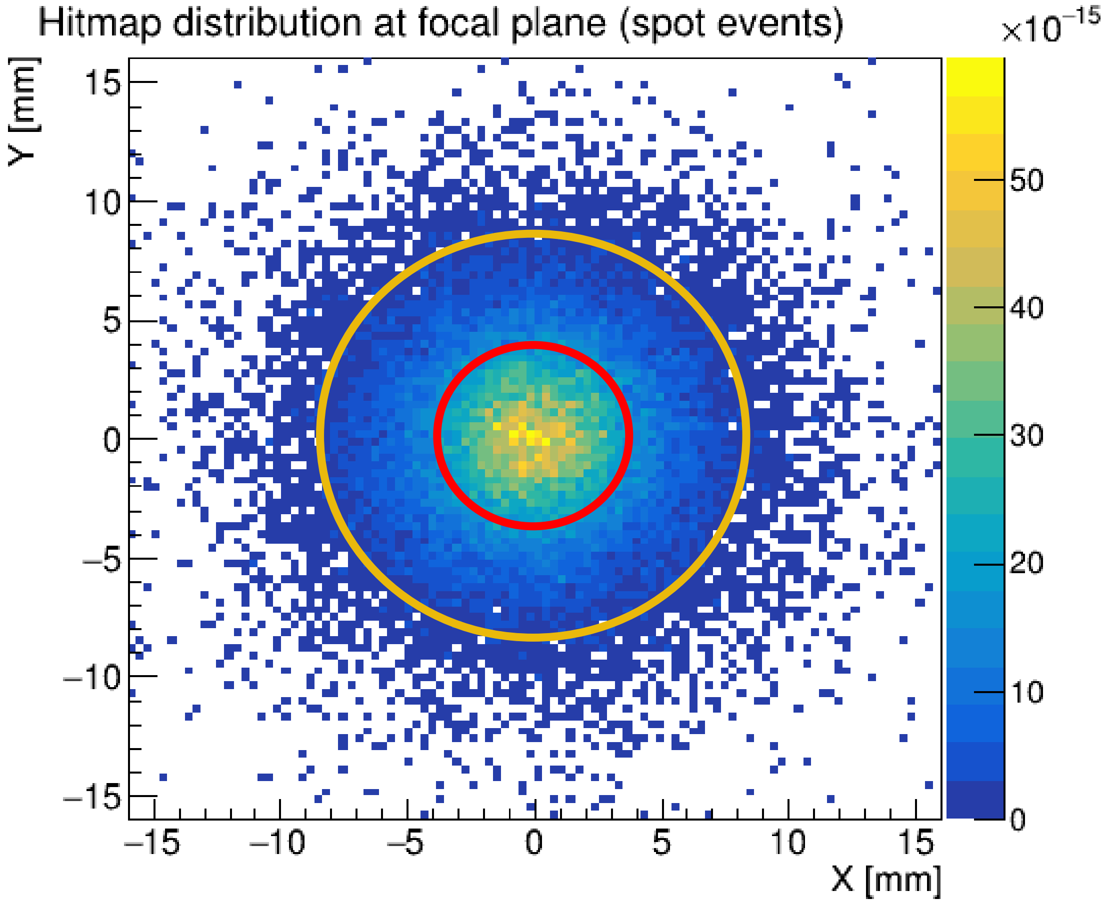
1. Get energy dependent transmission probability of different materials
2. Create a geometric mask

BABYIAXO – PERFECT ALIGNMENT



RESULTS PERFECT ALIGNMENT

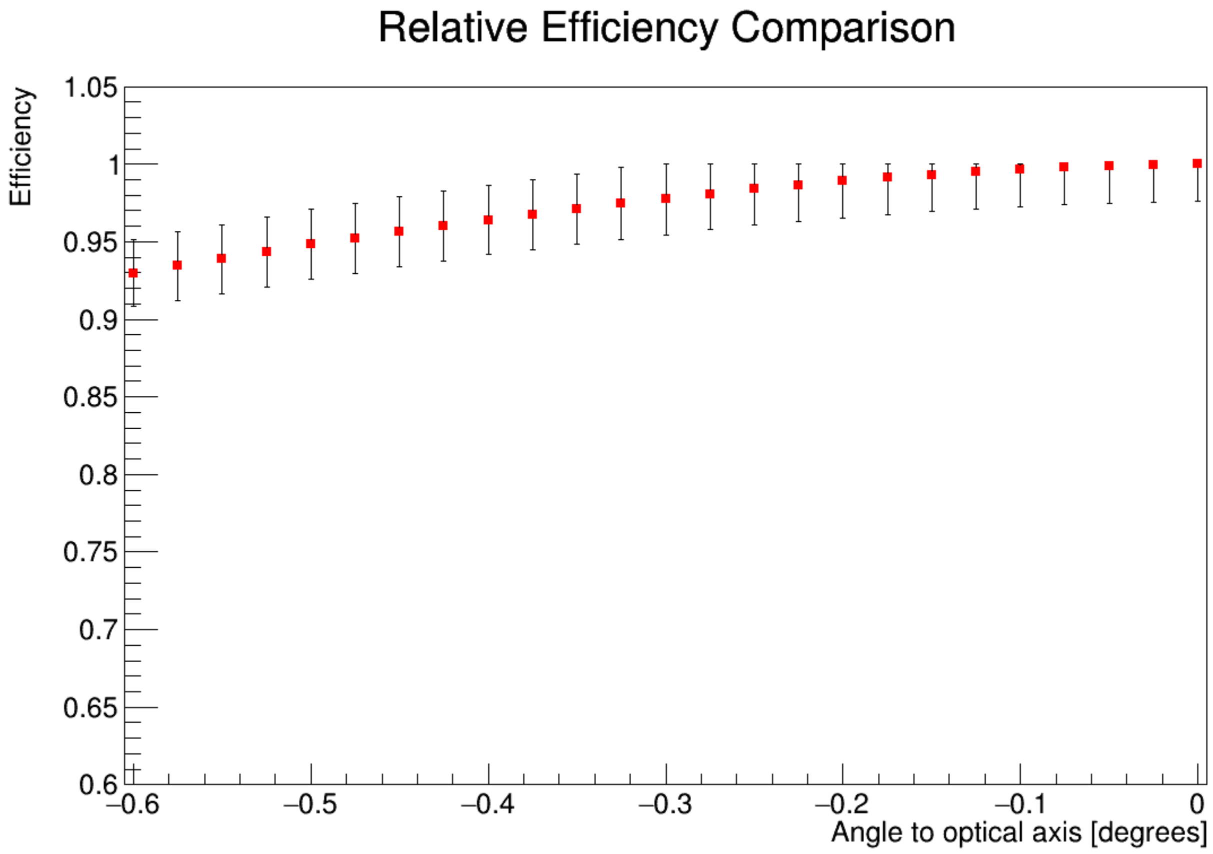
- Run with 100 000 events
- Solar flux: Primakoff
- Vacuum stage
- Optics: XMM optics
- Results here done with REST v2.3.15



HEW=7.83mm W90=16.83mm
HEW=3.59′ W90=7.714′

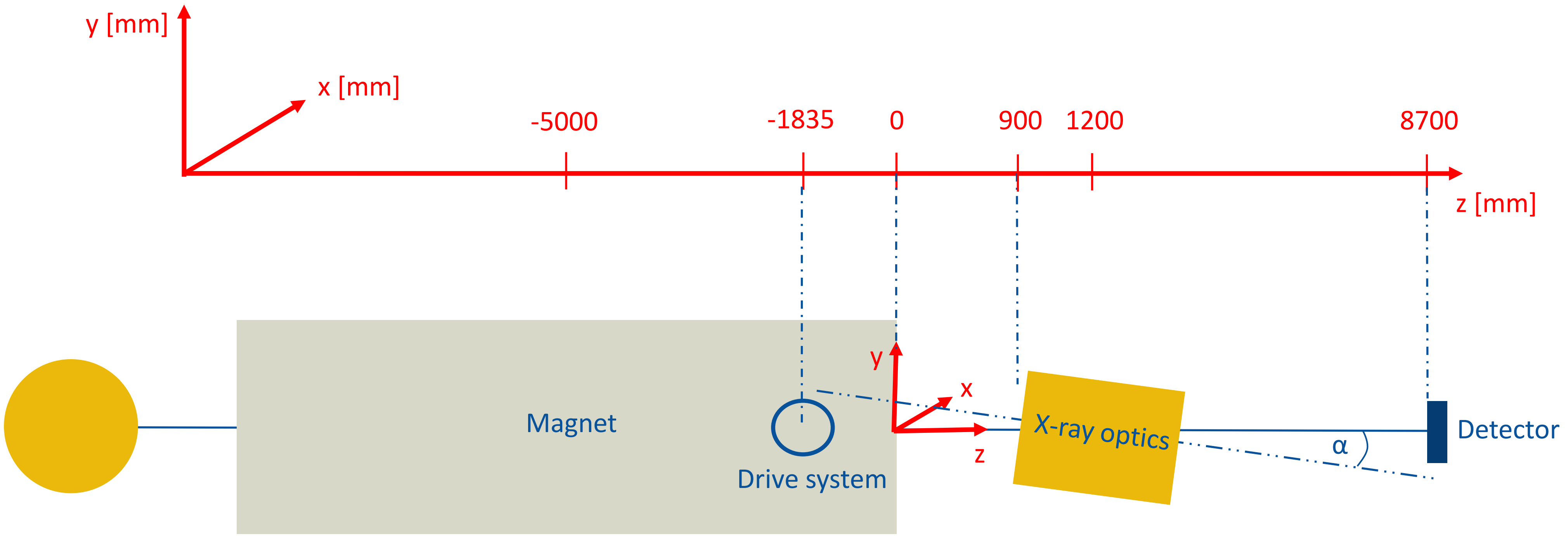
ACCEPTANCE STUDY

1. Internal:
   - Individual rotation of magnet and optics around their own center
   - Magnet, optics and detector displacement
2. External:
   - Misalignment effects due to gravity

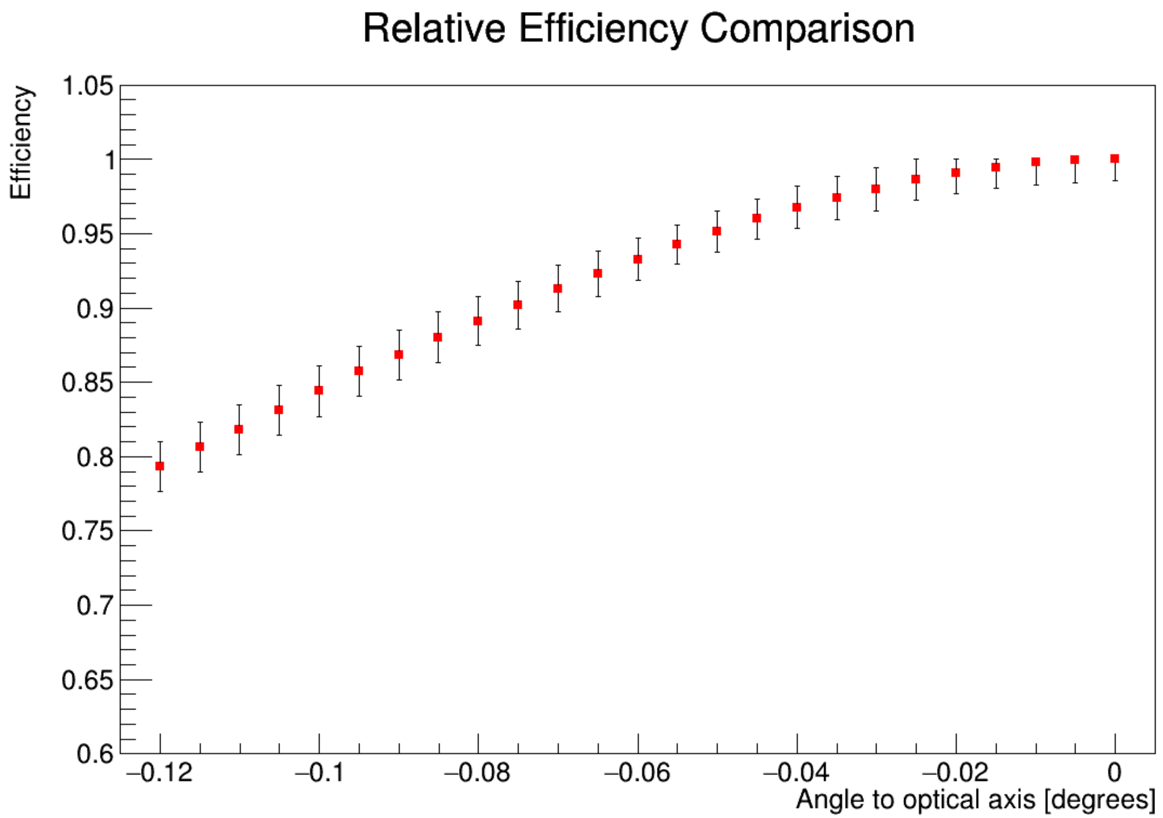


Internal magnet rotation downwards

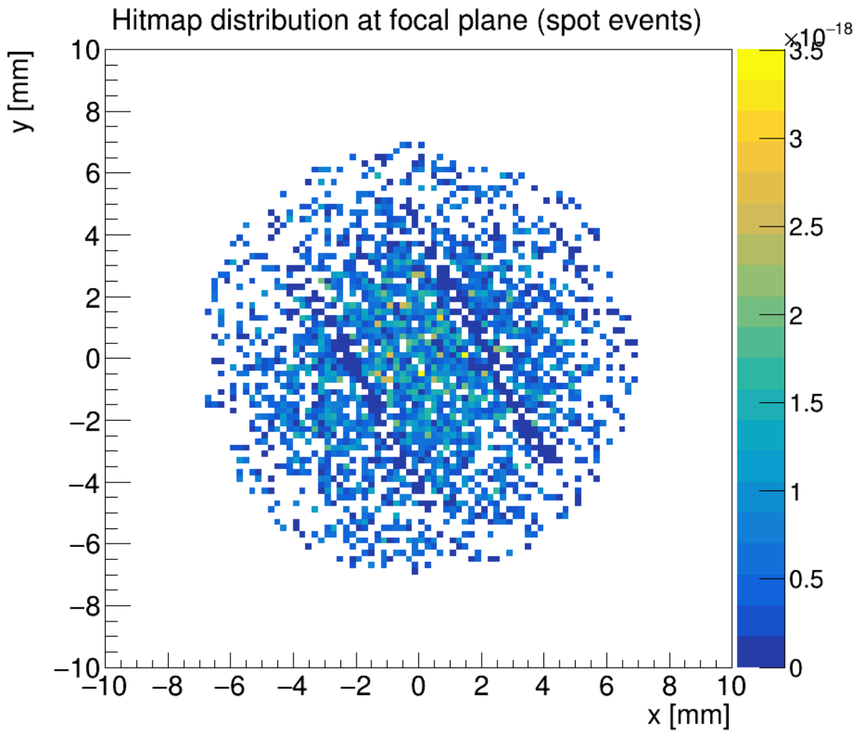
INTERNAL ROTATION X-RAY OPTICS



INTERNAL OPTICS ROTATION



Internal optics rotation downwards



Optics rotation around its center by 0.12°

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RESULTS INTERNAL

Individual acceptance magnet	
Rotation $\alpha_{\text{pitch}}(99\%)$ [°]	Rotation $\alpha_{\text{yaw}}(99\%)$ [°]
-0.19	-0.13
Deviation $y(99\%)$ [mm]	Deviation $x(99\%)$ [mm]
-24.76	-17.77

Magnet

RESULTS INTERNAL

Individual acceptance magnet	
Rotation $\alpha_{\text{pitch}}(99\%)$ [°]	Rotation $\alpha_{\text{yaw}}(99\%)$ [°]
-0.19	-0.13
Deviation $y(99\%)$ [mm]	Deviation $x(99\%)$ [mm]
-24.76	-17.77

Individual acceptance XMM optics	
Rotation $\alpha_{\text{pitch}}(99\%)$ [°]	Rotation $\alpha_{\text{yaw}}(99\%)$ [°]
-0.021	-0.017
Deviation $y(99\%)$ [mm]	Deviation $x(99\%)$ [mm]
-1.09	-1.02

Magnet

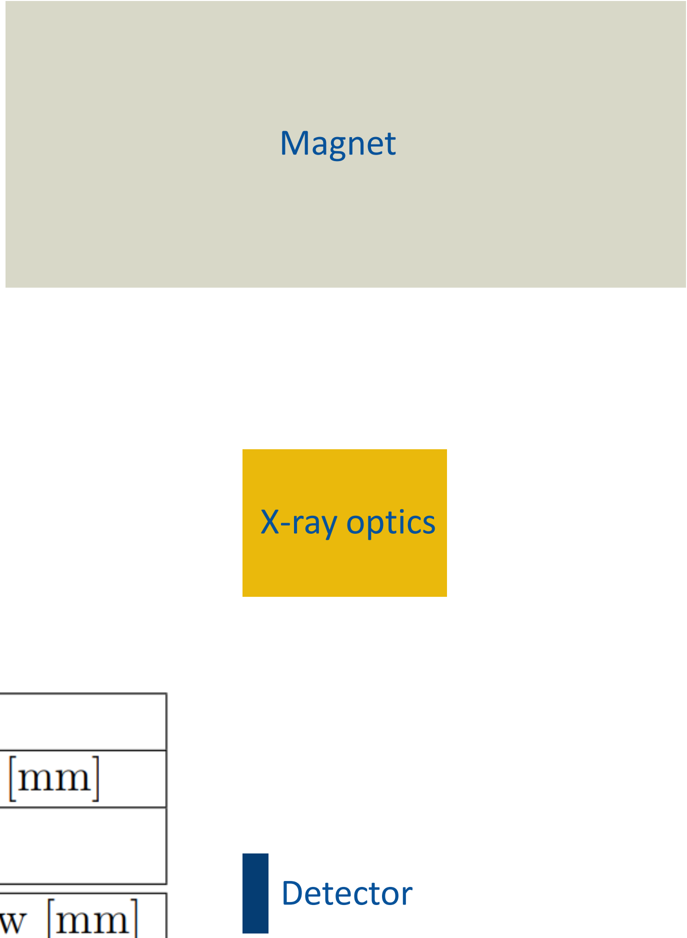
X-ray optics

RESULTS INTERNAL

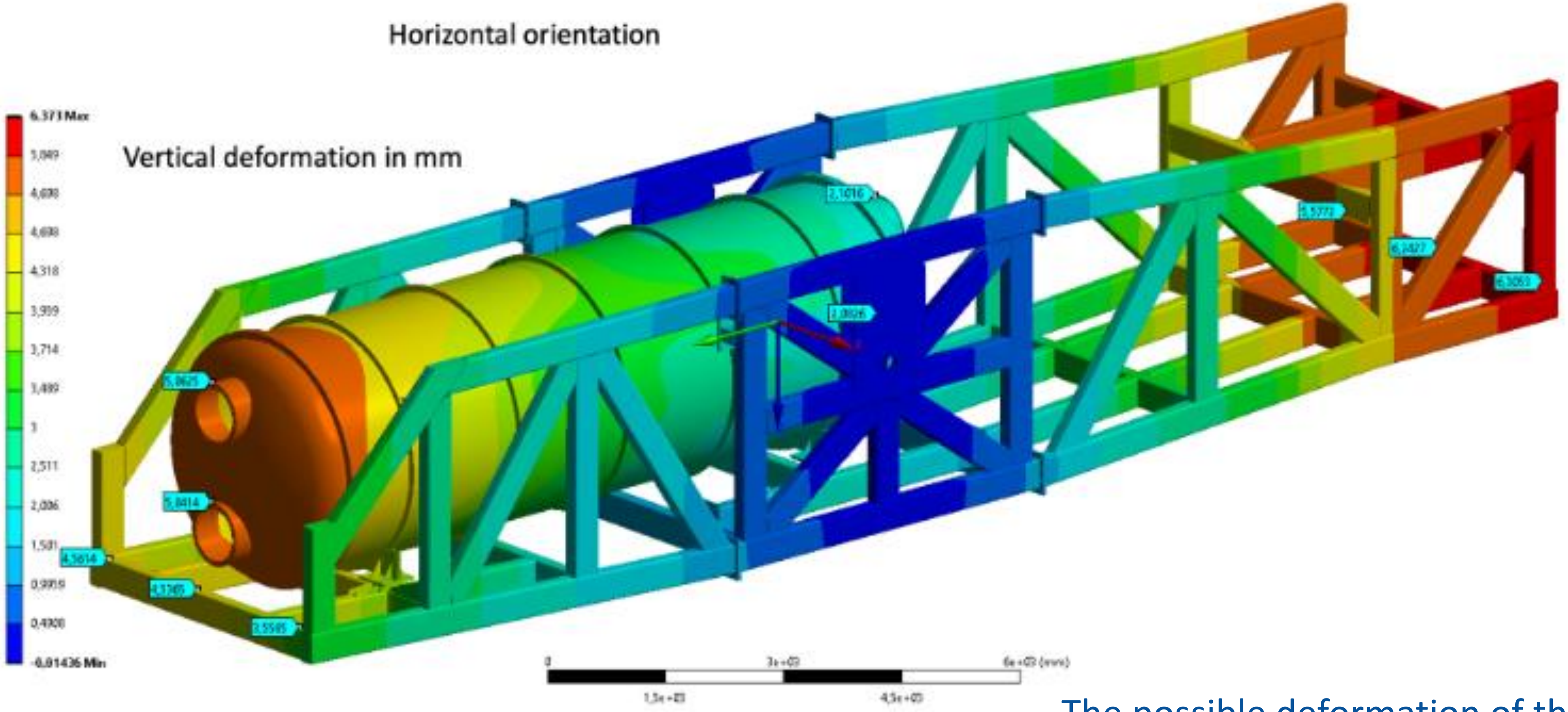
Individual acceptance magnet	
Rotation $\alpha_{\text{pitch}}(99\%)$ [°]	Rotation $\alpha_{\text{yaw}}(99\%)$ [°]
-0.19	-0.13
Deviation $y(99\%)$ [mm]	Deviation $x(99\%)$ [mm]
-24.76	-17.77

Individual acceptance XMM optics	
Rotation $\alpha_{\text{pitch}}(99\%)$ [°]	Rotation $\alpha_{\text{yaw}}(99\%)$ [°]
-0.021	-0.017
Deviation $y(99\%)$ [mm]	Deviation $x(99\%)$ [mm]
-1.09	-1.02

Individual acceptance detector	
$y(99\%)$ GridPix window [mm]	$x(99\%)$ GridPix window [mm]
-1.04	-1.06
$y(99\%)$ Micromegas window [mm]	$x(99\%)$ Micromegas window [mm]
-1.22	-1.25

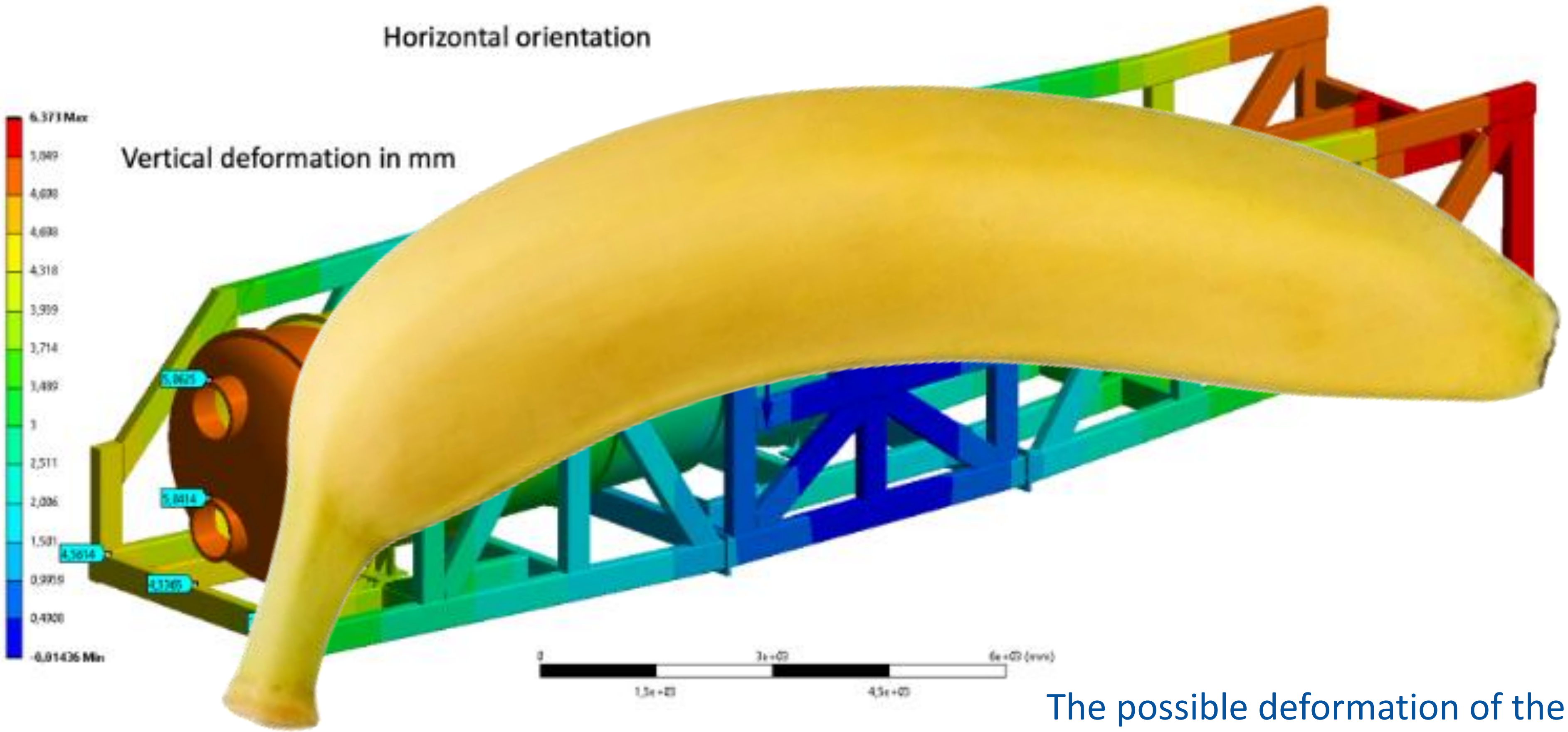


POSSIBLE GRAVITATIONAL EFFECTS



The possible deformation of the setup due to gravity at 0°

POSSIBLE GRAVITATIONAL EFFECTS



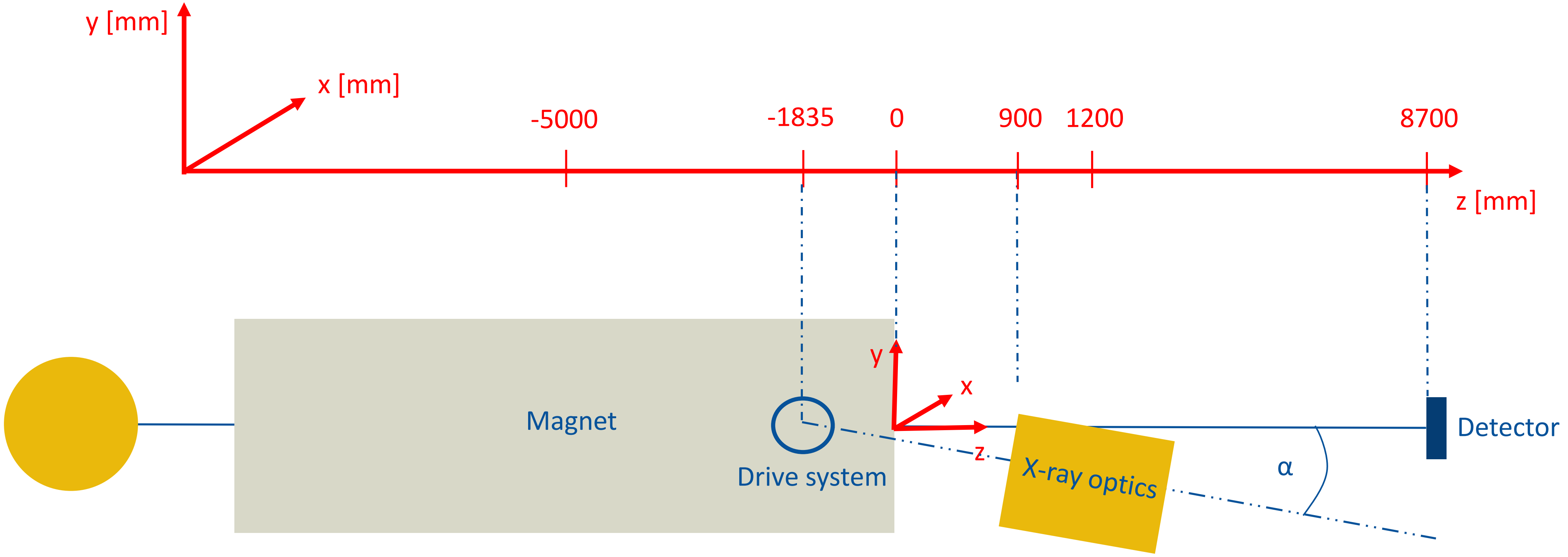
The possible deformation of the setup due to gravity at 0°

POSSIBLE GRAVITATIONAL EFFECTS

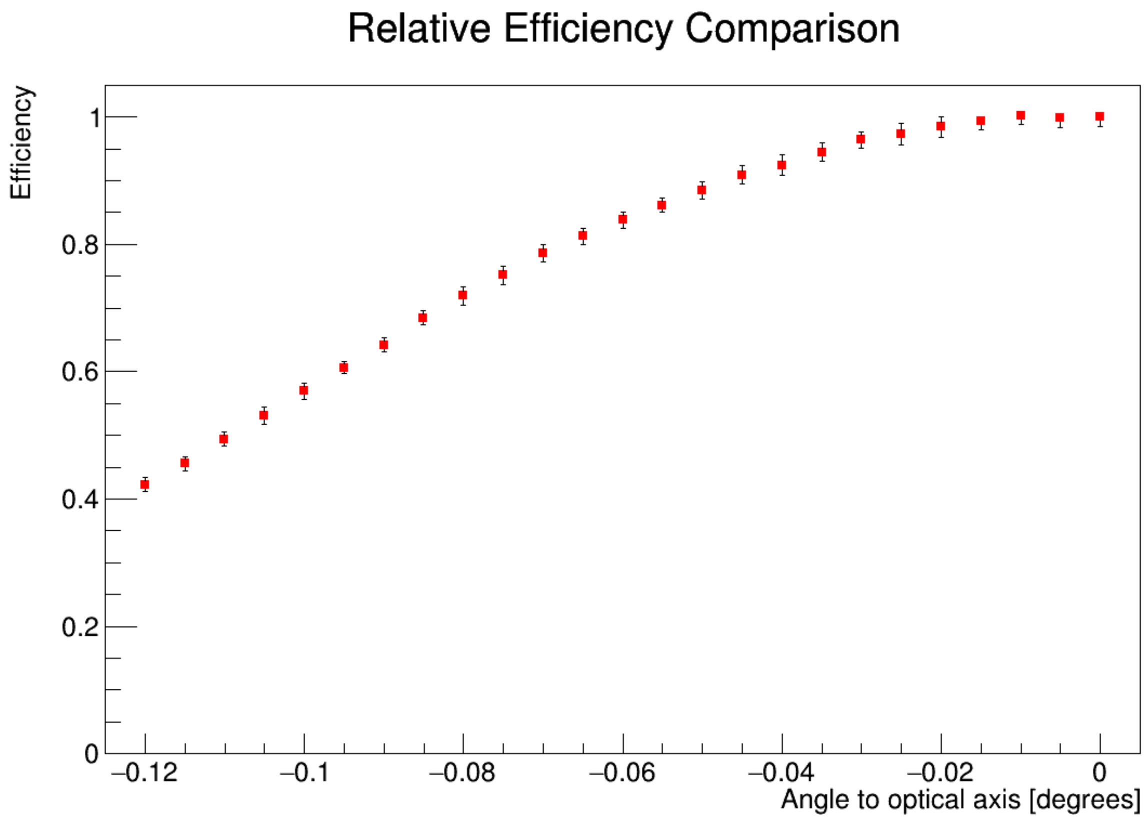
Support Frame Deformations (mm)						
	Magnet side					
Tilt	Ansys[a)]	Ansys[b)]	Comsol	RStab	Average	Std Dev
0°	4.5	4.1	3.9	4.9	4.4	0.4
25°	4.6	3.9	3.8	4.9	4.3	0.5
-25°	3.5	3.6	3.3	3.8	3.5	0.2
$\Delta(25-0)$	0.1	-0.2	-0.1	0.0	-0.1	0.1
$\Delta(-25-0)$	-1.0	-0.5	-0.6	-1.1	-0.8	0.3
	Detector side					
Tilt	Ansys[a)]	Ansys[b)]	Comsol	RStab	Average	Std Dev
0°	6.2	6.0	5.9	4.8	5.8	0.1
25°	4.4	5.3	4.3	3.0	4.3	0.4
-25°	6.4	5.6	6.1	5.3	5.9	0.4
$\Delta(25-0)$	-1.8	-0.7	-1.6	-1.8	-1.5	0.5
$\Delta(-25-0)$	0.2	-0.4	0.2	0.5	0.1	0.3

The possible deformation of the setup due to gravity

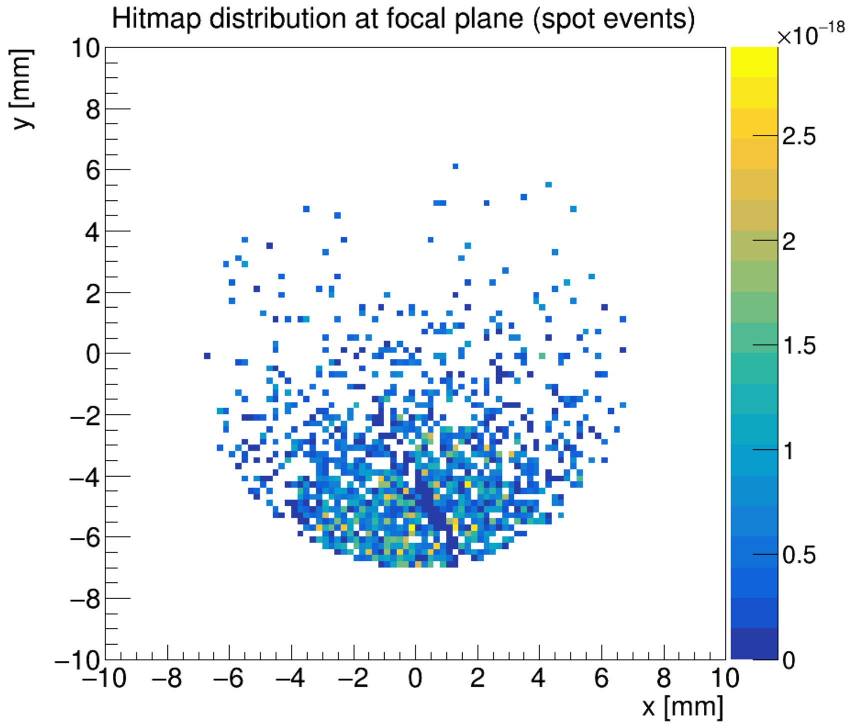
DEFORMATION DUE TO GRAVITY ONLY OPTICS



DEFORMATION DUE TO GRAVITY ONLY OPTICS

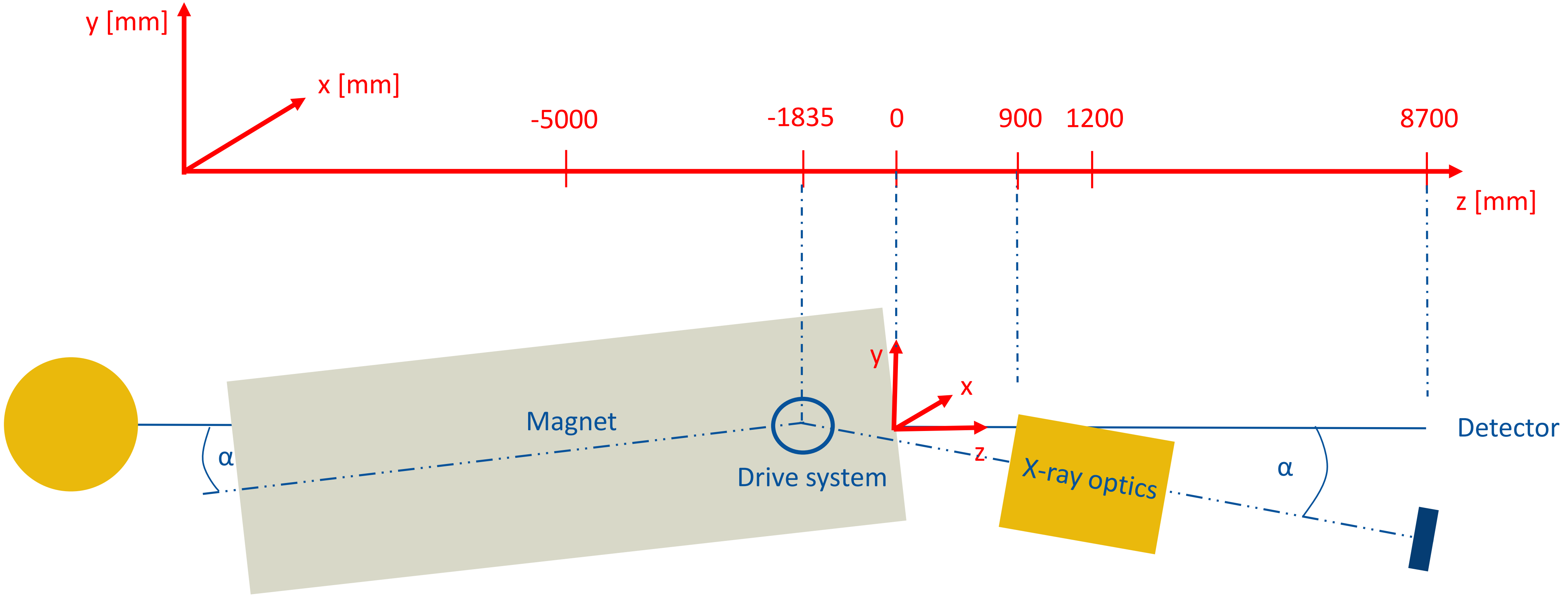


Optics rotation around the systems center

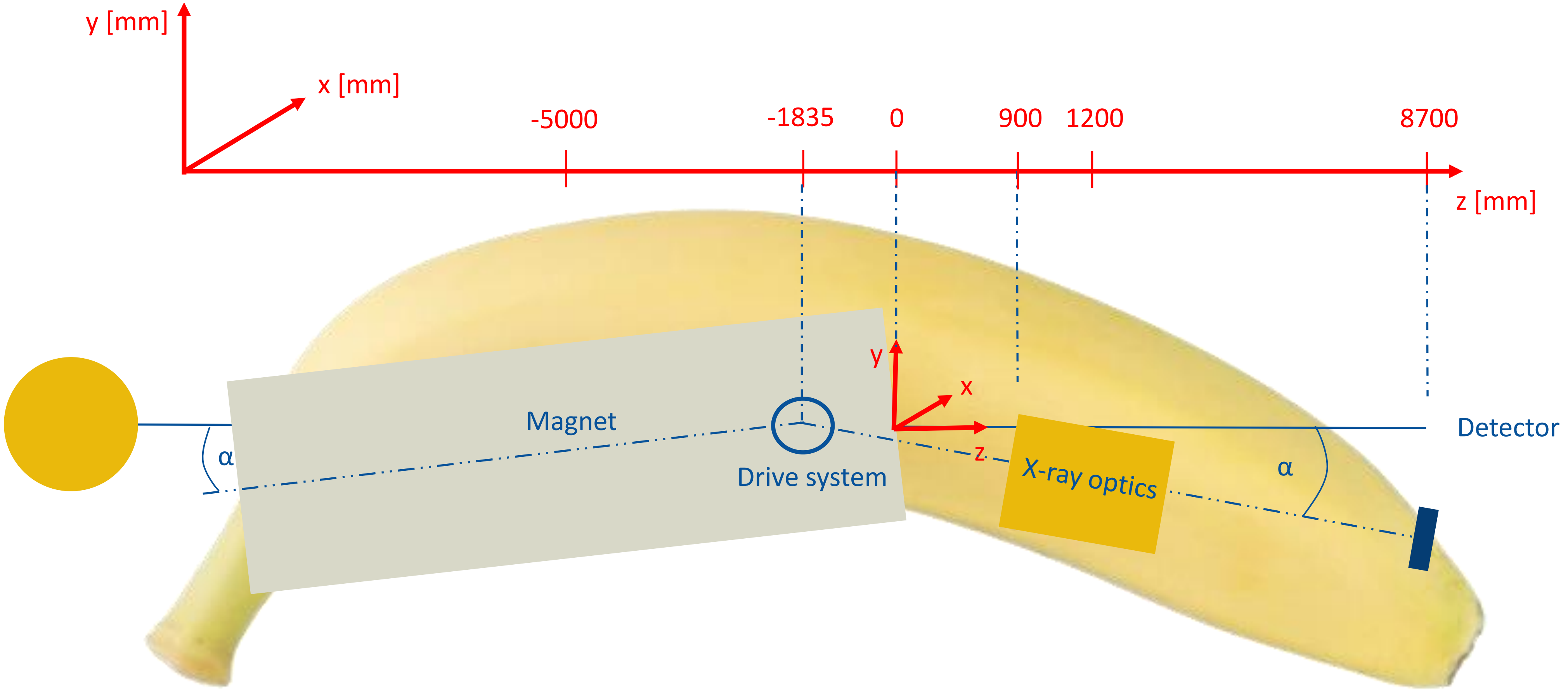


Optics rotation around system center by 0.12°

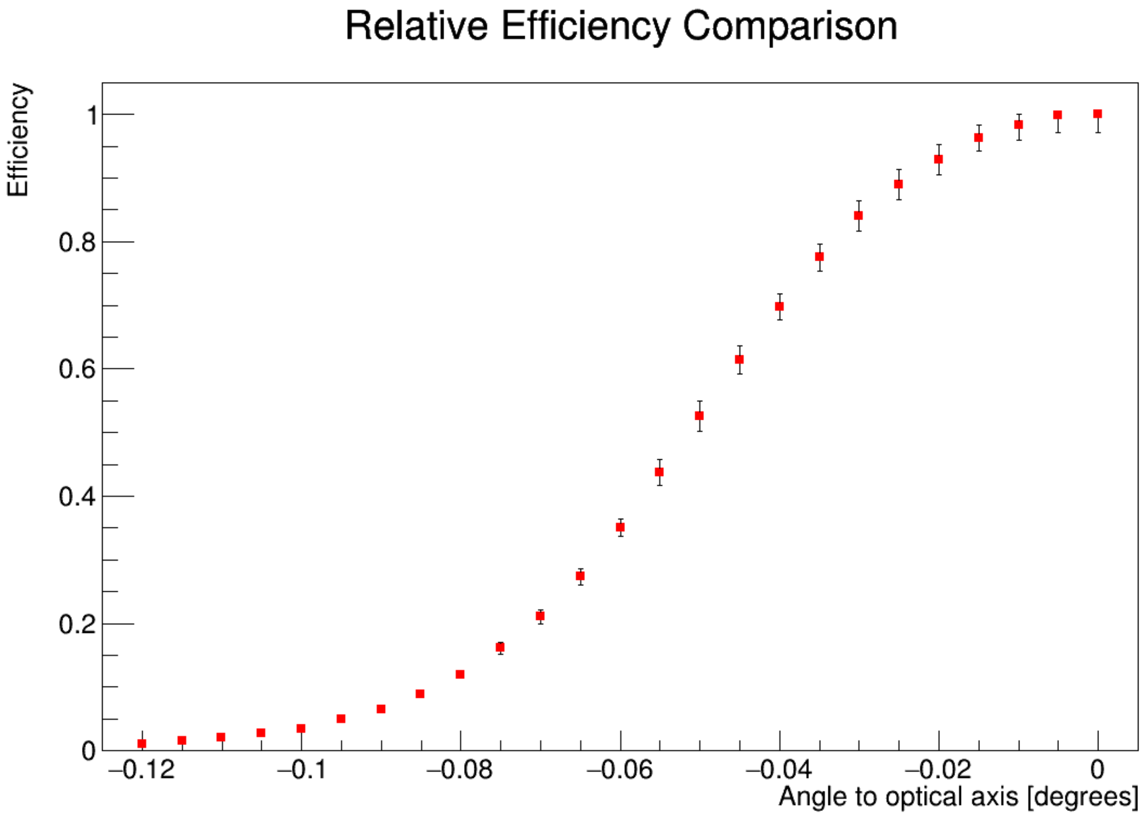
DEFORMATION DUE TO GRAVITY



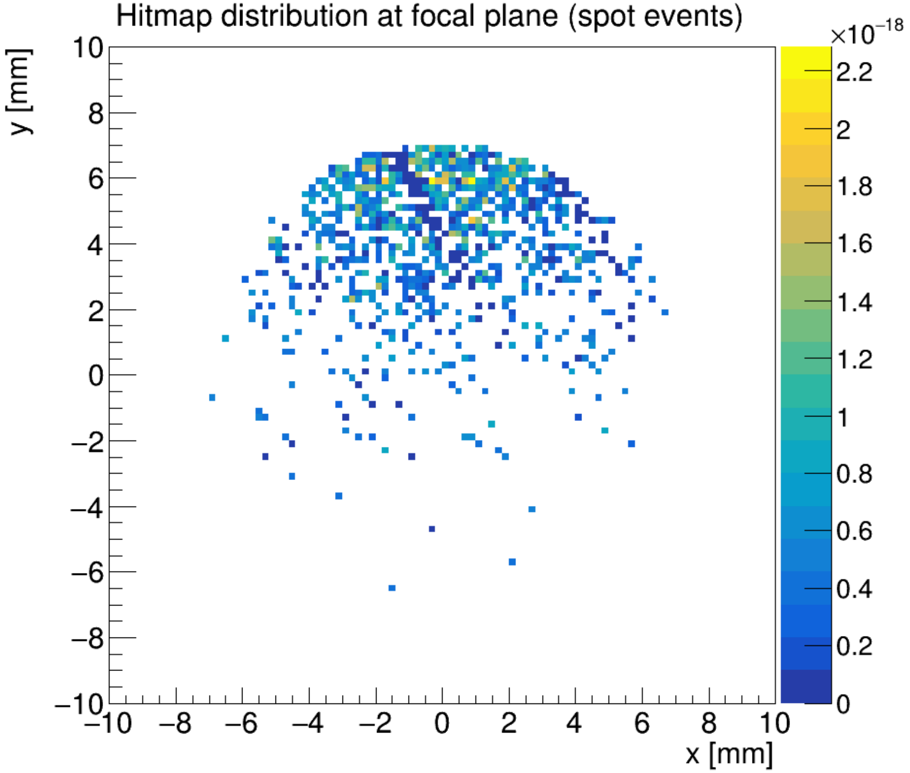
DEFORMATION DUE TO GRAVITY



DEFORMATION DUE TO GRAVITY

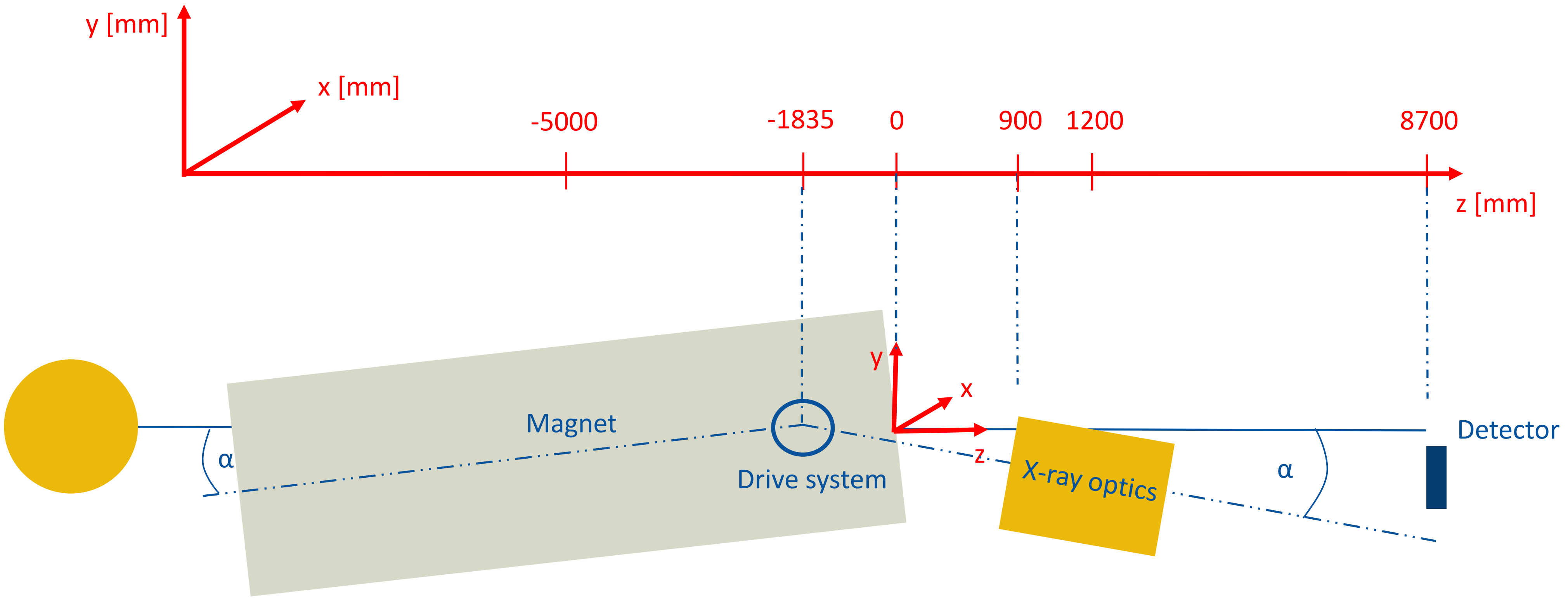


System rotation banana shaped

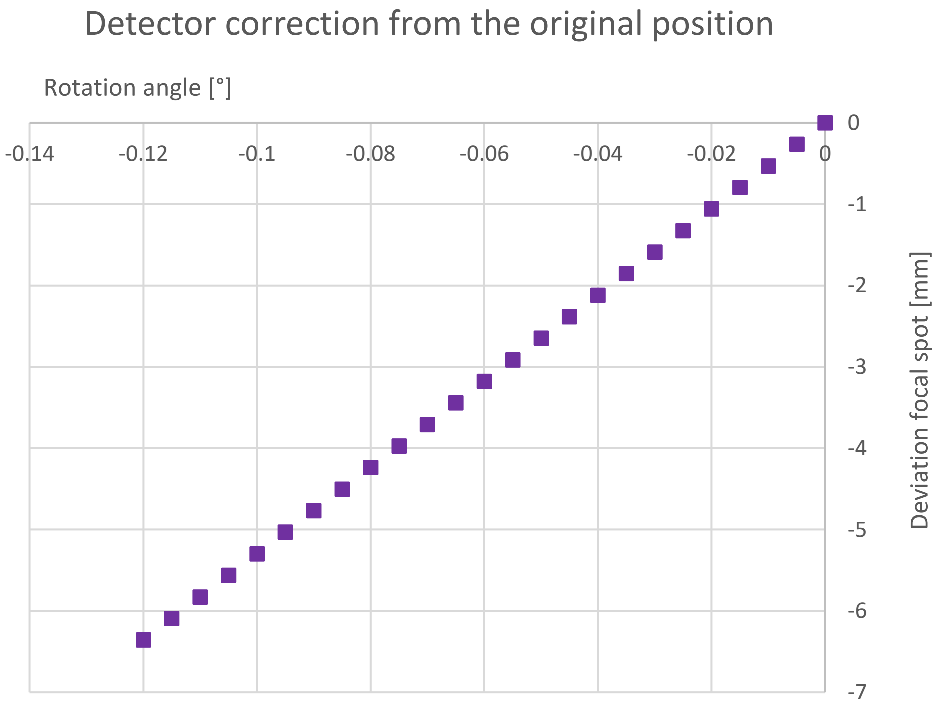


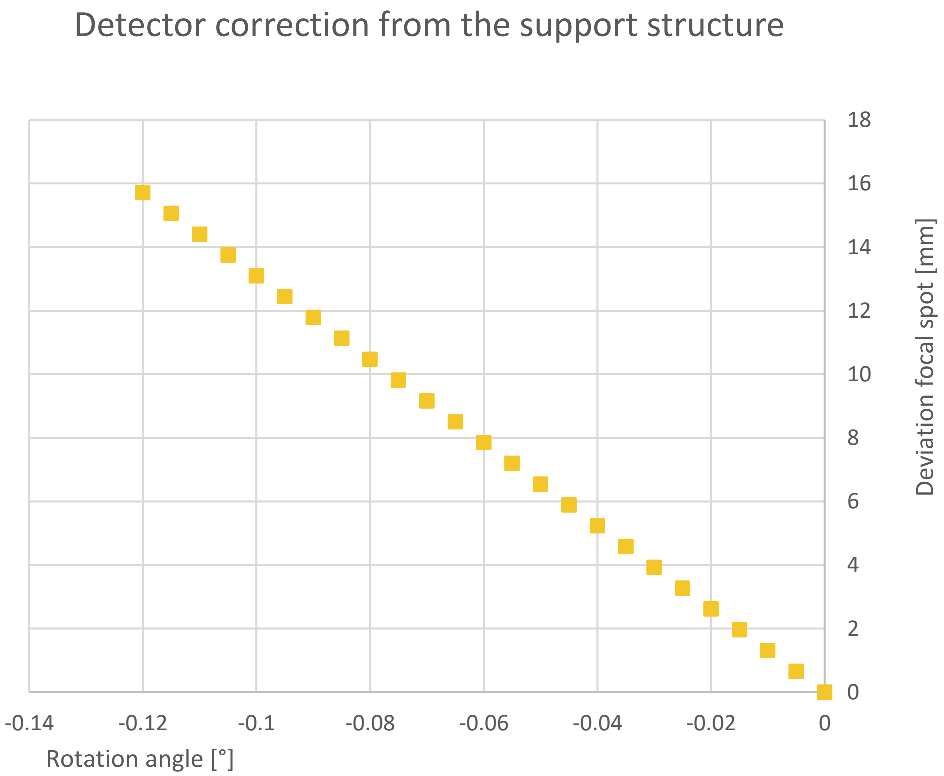
Focal plane distribution of the system rotation by 0.06°

DEFORMATION DUE TO GRAVITY WITH DETECTOR CORRECTION

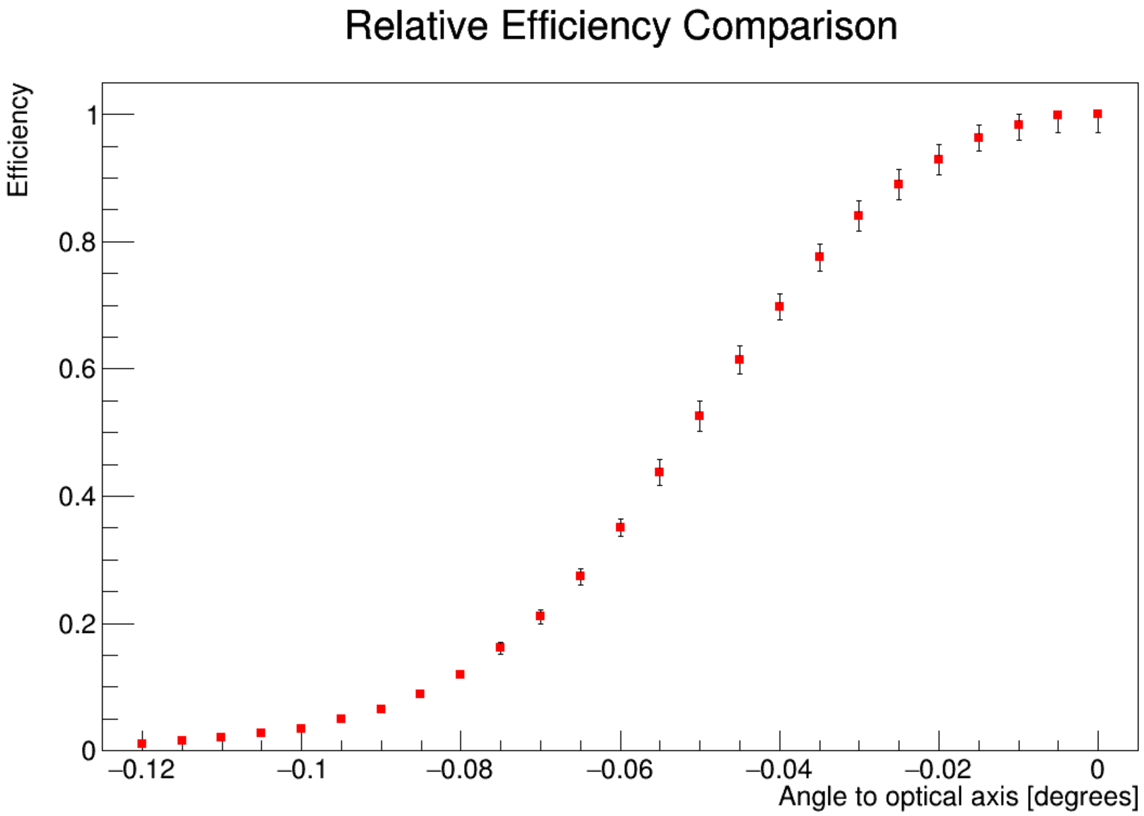


DEFORMATION DUE TO GRAVITY – DETECTOR CORRECTION

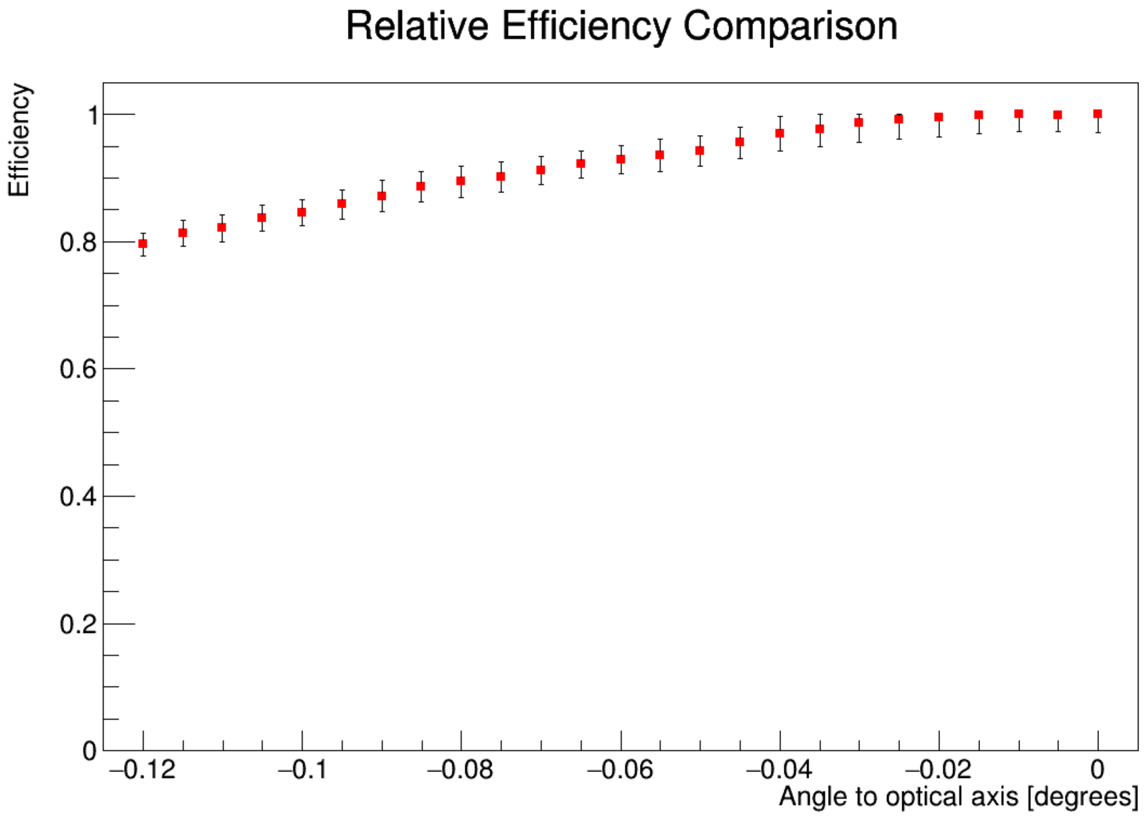




DEFORMATION DUE TO GRAVITY



System rotation banana shaped



System rotation banana shaped corrected detector

RESULTS DEFORMATION DUE TO GRAVITY

Magnet side				
	Magnet	Magnet and optics	All	Detector corrected
$\alpha(99\%)$ [°]	-0.19	-0.016	-0.01	-0.025
$\Delta y(99\%)$ [mm]	-27.25	-2.23	-1.39	-3.58
$\alpha(95\%)$ [°]	x	-0.035	-0.018	-0.049
$\Delta y(95\%)$ [mm]	x	-4.94	-2.58	-7.00

Detector side				
	XMM optics	Magnet and optics	All	Detector corrected
$\alpha(99\%)$ [°]	-0.0175	-0.016	-0.01	-0.025
$\Delta y(99\%)$ [mm]	-3.22	-2.87	-1.8	-4.61
$\alpha(95\%)$ [°]	x	-0.035	-0.018	-0.049
$\Delta y(95\%)$ [mm]	x	-6.38	-3.33	-9.03

RESULTS DEFORMATION DUE TO GRAVITY

Support Frame Deformations (mm)						
	Magnet side					
Tilt	Ansys[a)]	Ansys[b)]	Comsol	RStab	Average	Std Dev
0°	4.5	4.1	3.9	4.9	4.4	0.4
25°	4.6	3.9	3.8	4.9	4.3	0.5
−25°	3.5	3.6	3.3	3.8	3.5	0.2
$\Delta(25-0)$	0.1	-0.2	-0.1	0.0	-0.1	0.1
$\Delta(-25-0)$	-1.0	-0.5	-0.6	-1.1	-0.8	0.3
	Detector side					
Tilt	Ansys[a)]	Ansys[b)]	Comsol	RStab	Average	Std Dev
0°	6.2	6.0	5.9	4.8	5.8	0.1
25°	4.4	5.3	4.3	3.0	4.3	0.4
−25°	6.4	5.6	6.1	5.3	5.9	0.4
$\Delta(25-0)$	-1.8	-0.7	-1.6	-1.8	-1.5	0.5
$\Delta(-25-0)$	0.2	-0.4	0.2	0.5	0.1	0.3

[mm]
Detector corrected
-0.025
-3.58
-0.049
-7.00

[mm]
Detector corrected
-0.025
-4.61
-0.049
-9.03

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REST RAYTRACER COLLABORATION

Solar axion flux implemented by:

Sebastian Hoof

Lennert Thormahlen

Maurizio Gianotti

Solar flux: https://github.com/sebhoof/SolarAxionFlux

X-ray optics implemented by:

Javier Galán

Johanna von Oy

Ray tracer

https://github.com/rest-for-physics/axionlib

Magnetic field implemeted by:

Kresimir Jakovcic

Nikolay Bikovskiy

Detector windows and masks implemented by:

Javier Galán

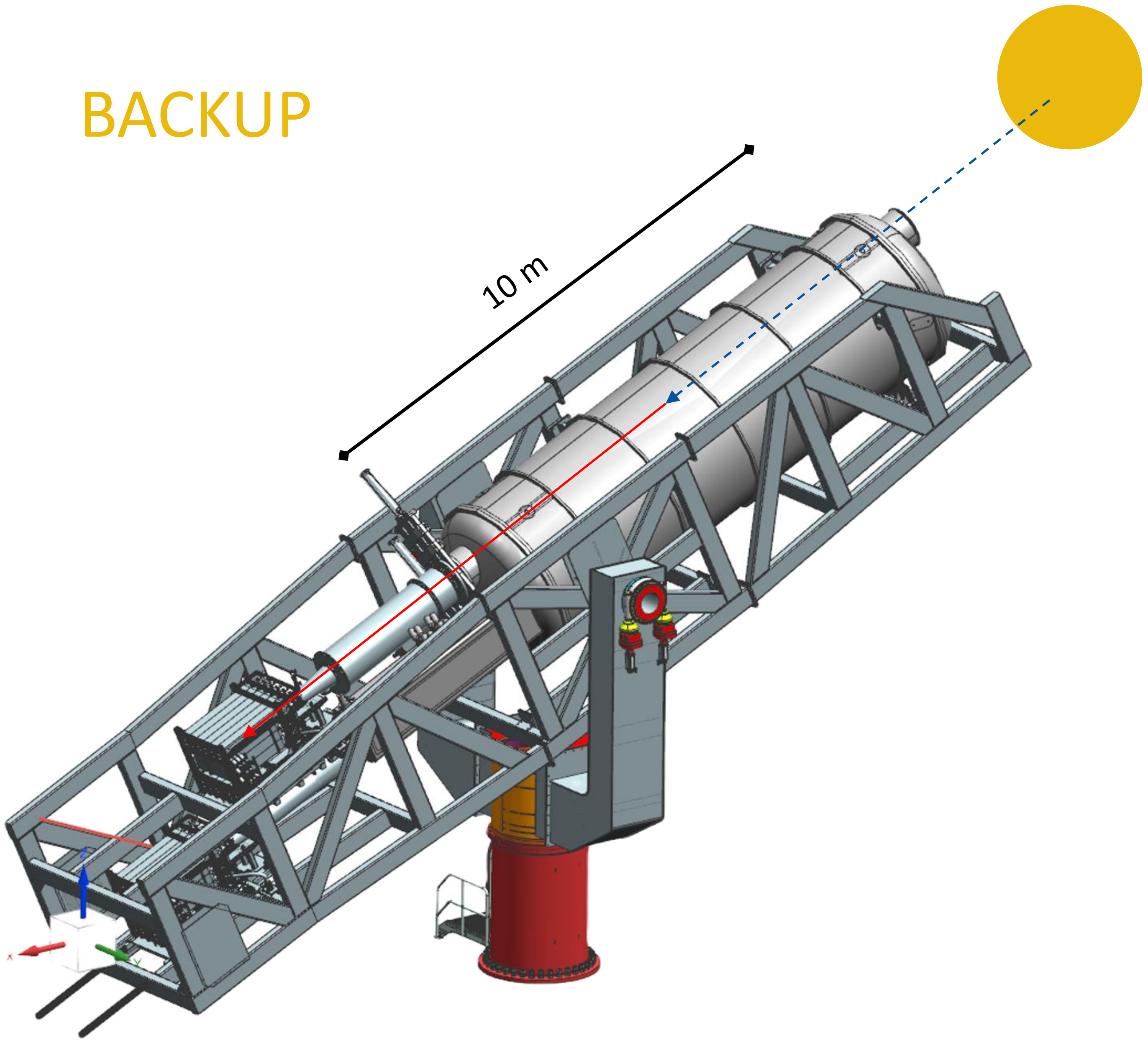
Johanna von Oy

SUMMARY

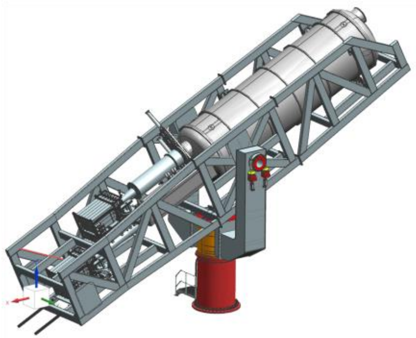
BabyIAXO simulated by the REST ray tracer:

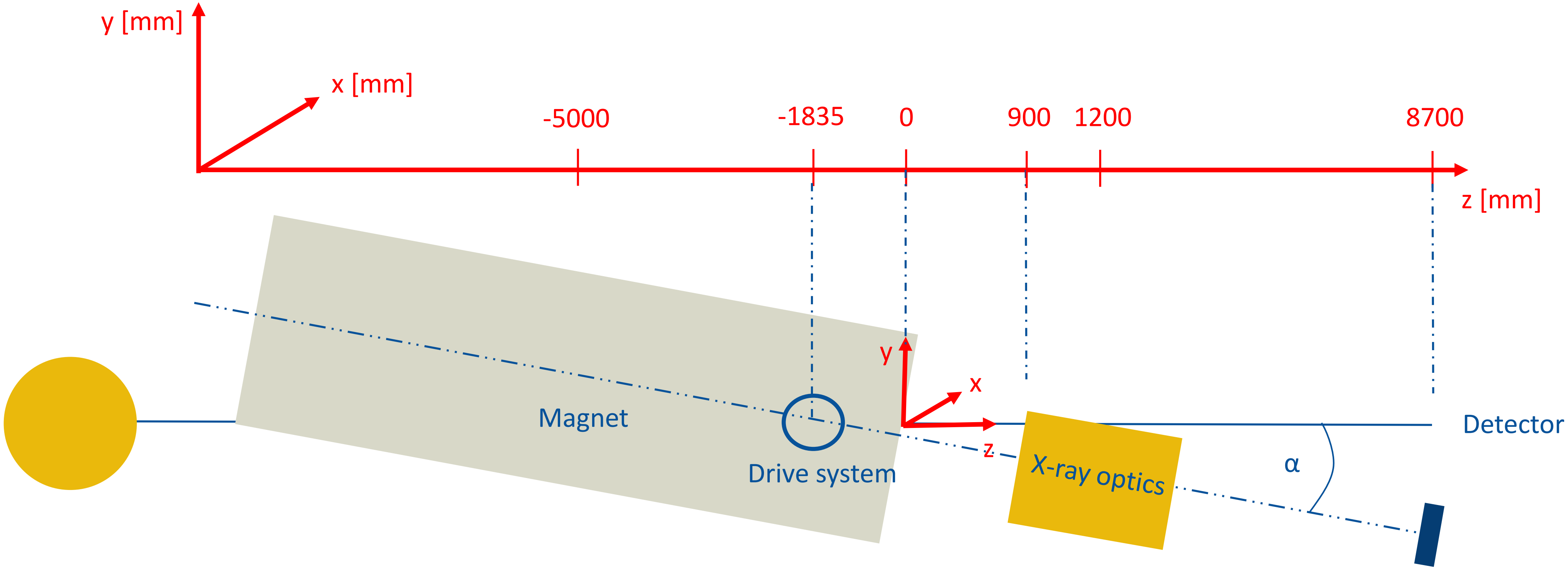
- Overview of acceptances of individual components: magnet, optics, detector
- Simulation of worst-case scenario due to gravitational effects
- Solution through detector movement

BACKUP

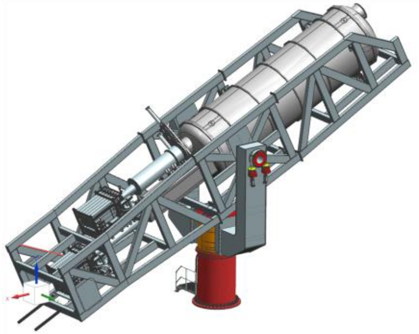


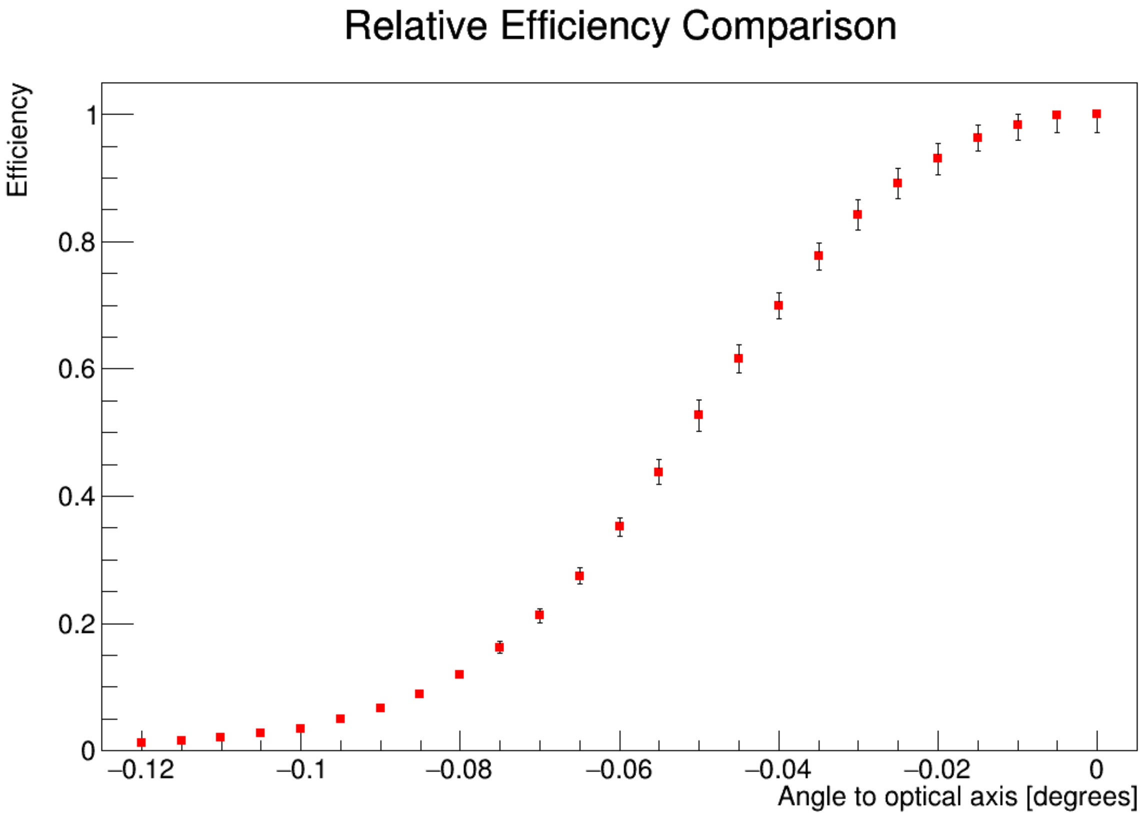
OVER ROTATION





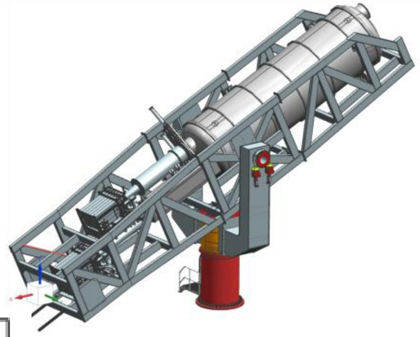
OVER ROTATION





System rotation downwards

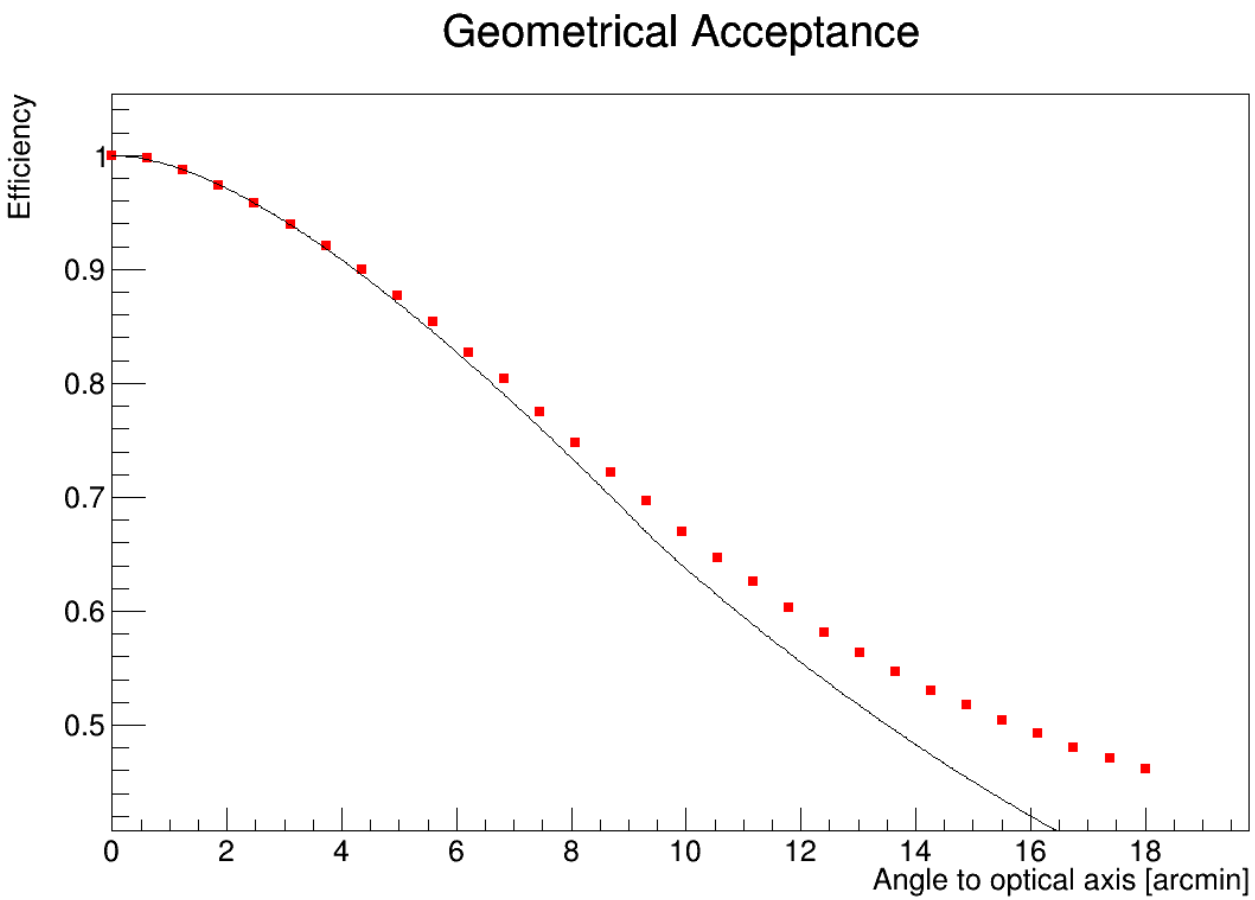
RESULTS DEFORMATION DUE TO GRAVITY

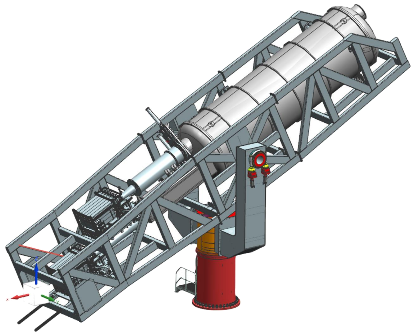


Magnet side				
	Magnet	Magnet and optics	All	Detector corrected
$\alpha(99\%)$ [°]	-0.19	-0.016	-0.01	-0.025
$\Delta y(99\%)$ [mm]	-27.25	-2.23	-1.39	-3.58
$\alpha(95\%)$ [°]	x	-0.035	-0.018	-0.049
$\Delta y(95\%)$ [mm]	x	-4.94	-2.58	-7.00

Detector side				
	XMM optics	Magnet and optics	All	Detector corrected
$\alpha(99\%)$ [°]	-0.0175	-0.016	-0.01	-0.025
$\Delta y(99\%)$ [mm]	-3.22	-2.87	-1.8	-4.61
$\alpha(95\%)$ [°]	x	-0.035	-0.018	-0.049
$\Delta y(95\%)$ [mm]	x	-6.38	-3.33	-9.03

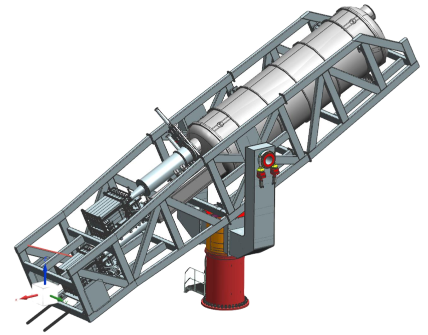
EFFICIENCY OF THE XMM AT 0.03 KEV

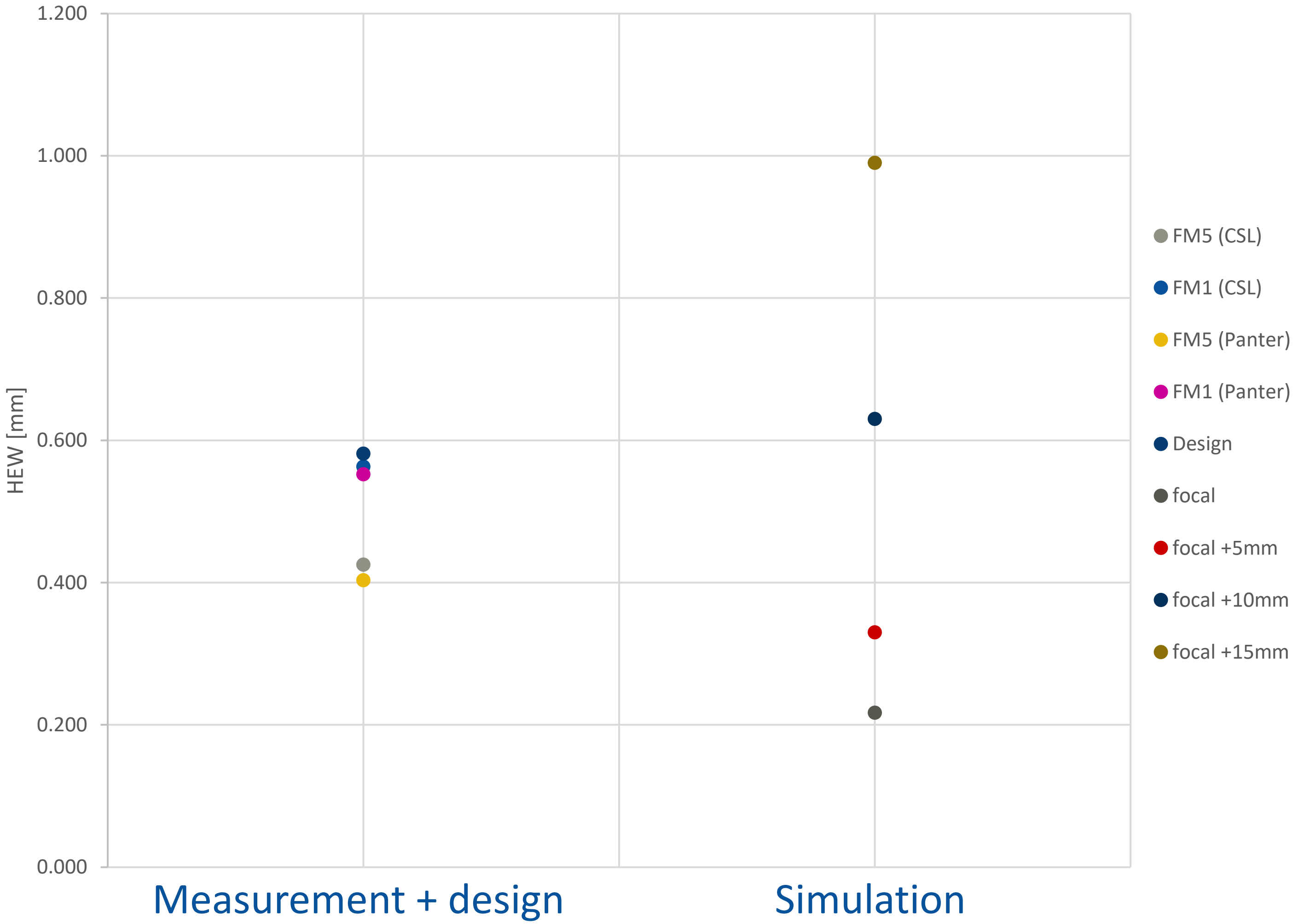




- Off axis test with an EUV source at Centre Spatial de Liège (CSL) in 1998 (black line)
- Rotation of the XMM optics in the ray tracer at 0.03 keV (red dots)

HEW: EXPERIMENT VS SIMULATION





- HEW: Diameter of a circle that includes half of the signal information
- Experimental data from CSL and Panter in the 90s

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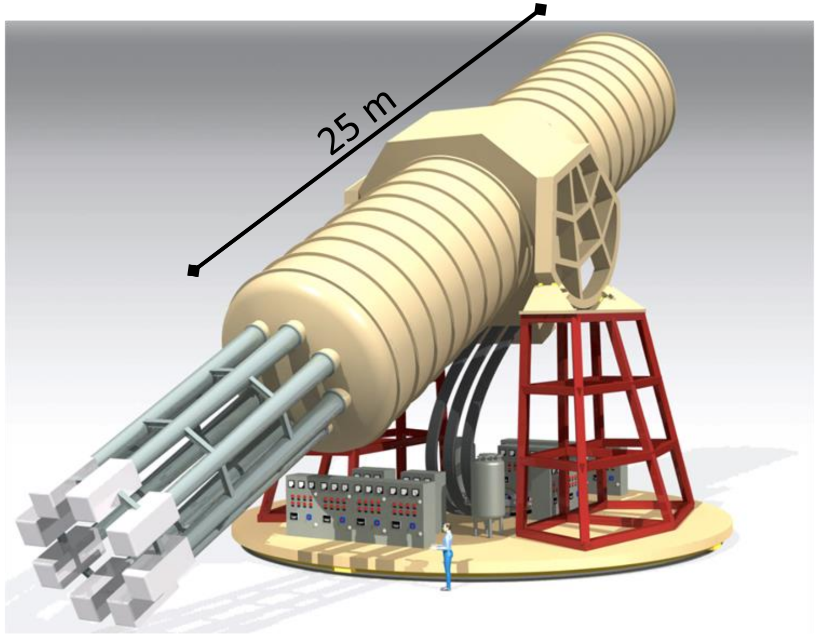
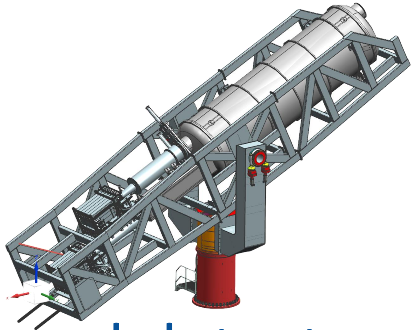
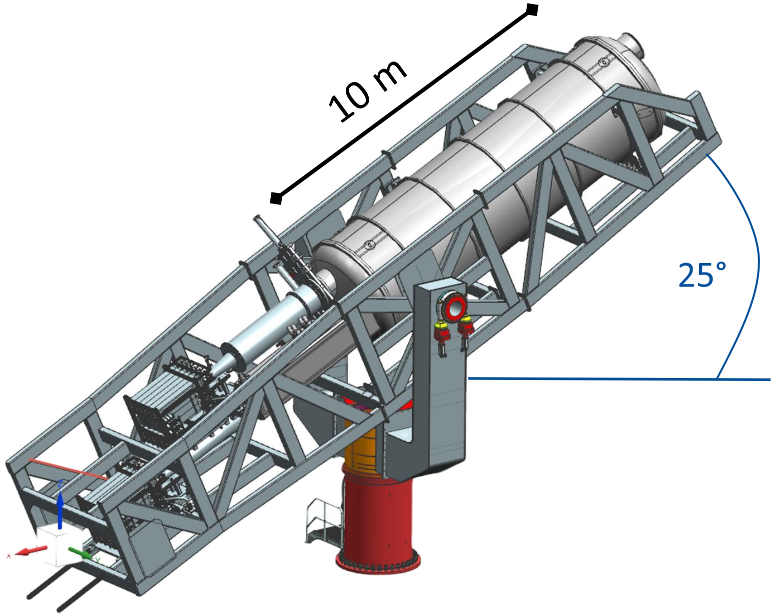
IAXO VS. BABYIAXO



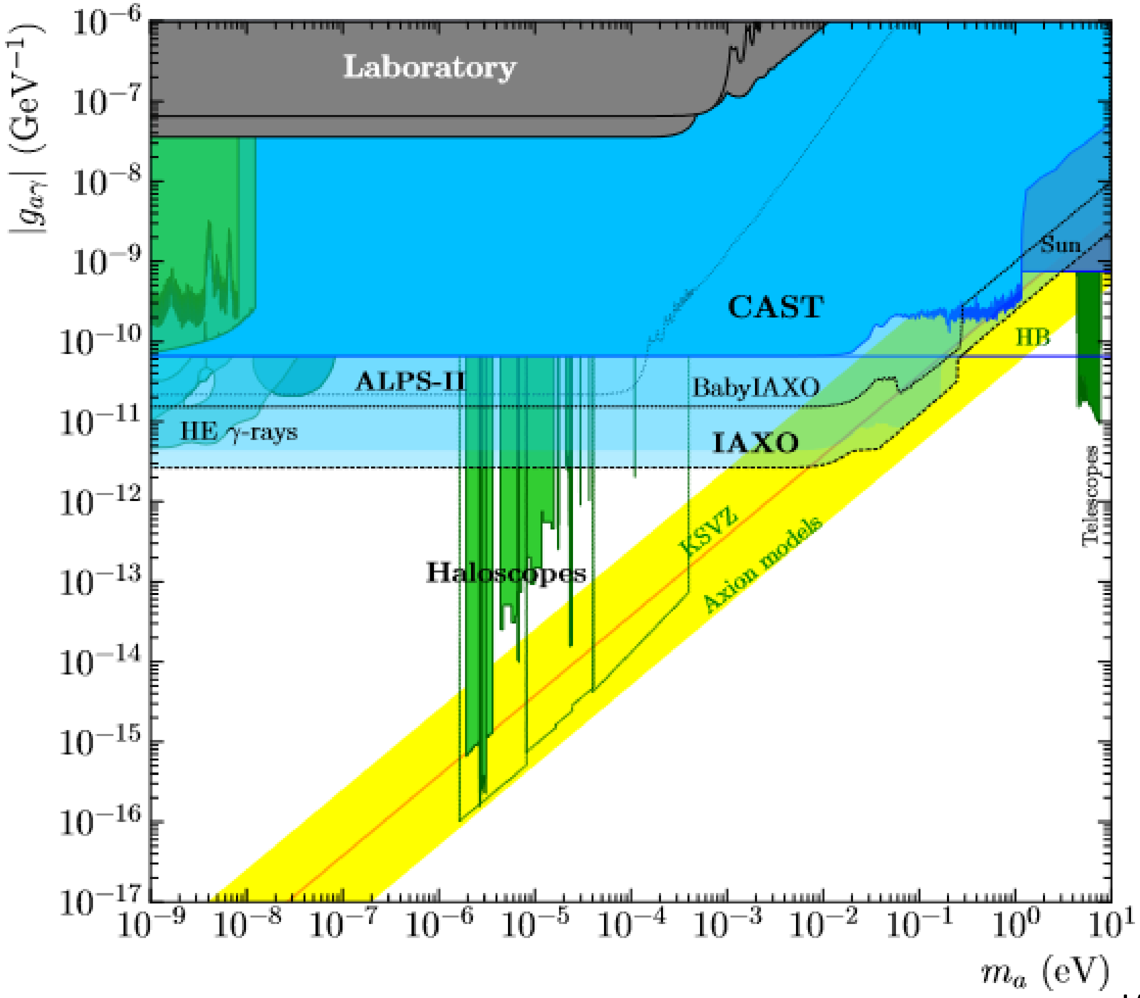
- 25m long magnet
- 8 bores with optics and detectors
- Peak magnetic field of 5.4 T

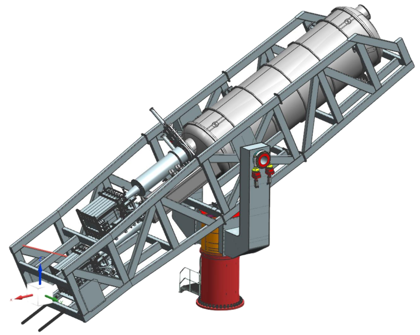
- 10m long magnet
- 2 bores with optics and detectors
- Peak magnetic field of 3.2 T





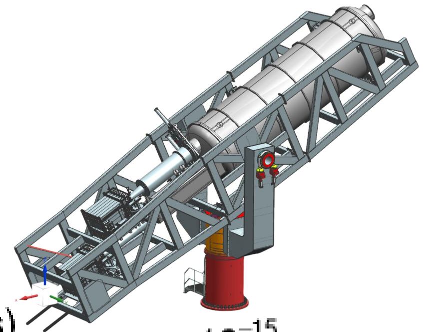
IAXO VS. BABYIAXO





IAXO collaboration 2020, arXiv:2010.12076

RESULTS PERFECT ALIGNMENT



- Run with 100 000 events
- Solar flux: Primakoff
- Vacuum stage
- Optics: XMM optics
- GridPix window
- Results here done with REST v2.3.15